Control on the emplacement of the andesite lava dome of the Soufriere Hills volcano, Montserrat by degassing-induced crystallization

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ABSTRACT

Lava solidification is controlled by two mechanisms: external cooling and gas exsolution, the latter inducing crystallization due to increasing liquidus temperature. The andesite lava dome of the Soufriere Hills Volcano, Montserrat, is an extrusion dominated by crystallization caused by gas exsolution where cooling is unimportant in controlling emplacement. In the magma chamber the magma has an estimated viscosity of 7×10^6 Pa s. During ascent, gas exsolution caused the magma to extrude in a highly crystalline state, with only 5–15% residual melt, viscosities in the range 10^{13}–10^{14} Pa s and mechanical strength > 1 MPa. Deformation can be heterogeneous with extrusion along shear zones. Rheological stiffening in the upper conduit also causes large overpressures, shallow seismicity, and cyclic patterns of dome extrusion. Gas-rich porphyritic andesites tend to be the least mobile kind of lava, because transition from magma into hot crystalline material was reached during ascent.

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Introduction

Two main mechanisms influence the emplacement and solidification of lava flows. In one mechanism external cooling forms a thickening solid crust and rheologically stiff zone which eventually causes lava movement to cease (Fink and Griffiths, 1990). Another mechanism is gas exsolution during ascent and extrusion, which causes the lava to solidify due to a large increase in the magma liquidus temperature. The implications of degassing-induced crystallization on lava emplacement and conduit flow are being increasingly recognized (e.g. Swanson *et al*., 1989; Cashman, 1992; Geschwind and Rutherford, 1995; Stix *et al*., 1997; Hammer *et al*., 1999; Melnik and Sparks, 1999; Nakada and Motomura, 1999; Voight *et al*., 1999; Sparks and Pinkerton, 1978:, Westrich *et al*., 1988).

Here we propose that degassing and contemporaneous crystallization from undercooled melt can be the dominant mechanism controlling the emplacement of some lava flows, particularly those of intermediate (andesite or dacite) composition, and that cooling is, in some circumstances, unimportant in their emplacement. The andesite lava dome of the Soufriere Hills volcano, Montserrat, provides an example of a lava dome dominated by degassing-induced crystallization. We present some rheological calculations and measurements on the andesite which show that viscosity increases by several orders of magnitude during decompression and gas exsolution. Field observations and experiments also show that the magma becomes strongly non-Newtonian with deformation localized along shear zones.

We contrast the behaviour of gas-rich porphyritic andesite with some rhyolite lavas. Rhyolitic obsidian lavas remain as an undercooled melt during extrusion, with much of the crystallization occurring after lava emplacement. In contrast, for gas-rich porphyritic andesite magma, the timescale of crystallization is sufficiently fast that extensive crystallization occurs within the conduit (Melnik and Sparks, 1999). As a consequence gas-rich andesite magmas can generate much less mobile lava than rhyolite, with a strong tendency to form steep sided domes and spines.

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Petrology and textures of the Soufriere Hills andesite

The Soufriere Hills andesite (58–61% SiO_2) contains 35–45 vol% phenocrysts (hornblende, plagioclase, orthopyroxene, titanomagnetite and minor quartz) and 15–20% microphenocrysts (lengths 80–300 μm). The groundmass (crystals < 80 μm) is composed of plagioclase microlites with subordinate pyroxene and Fe–Ti-oxide and a residual high-Si rhyolite glass (76–80 wt% SiO_2). Phase equilibria and studies of melt inclusions (Barclay *et al*., 1998) indicate that the magma at depth contained 4–5 wt% H_2O in the rhyolitic (73–74% SiO_2) melt phase. The temperature and water pressure conditions are estimated at 830–860°C and about 125–140 MPa (Murphy *et al.* 2000). The absence of groundmass hornblende and presence of clinopyroxene suggests that crystallization occurred as magma ascended and gas exsolved. Although there has been no significant variation in either the bulk composition of the magma or the proportions and compositions of the phenocrysts with time, the groundmass shows large variations in the degree of crystallinity and texture (Fig. 1).

The main controlling factor on groundmass textures is eruption rate. Samples which erupted in explosive eruptions and rapidly emplaced dome lobes, have a high glass content (25–30 vol%) (Fig. 1a). The rapidly erupted samples nevertheless have significant proportions of microlites (20%), indicating that crystallization occurred during magma ascent. Hornblende phenocrysts in rapidly erupted lava and in pumice are light green and pristine and lack reaction rims, indicating ascent of the magma in a few days or less (Devine *et al*., 1998). Samples, which are inferred to have spent significant amounts of time in the dome (typically a few weeks or months), have a highly crystalline fine-grained groundmass (Fig. 1b) and much less glass (5–15 vol%). Cristobalite (3–15%) occurs as a fine devitrification product of glass and vapour precipitate

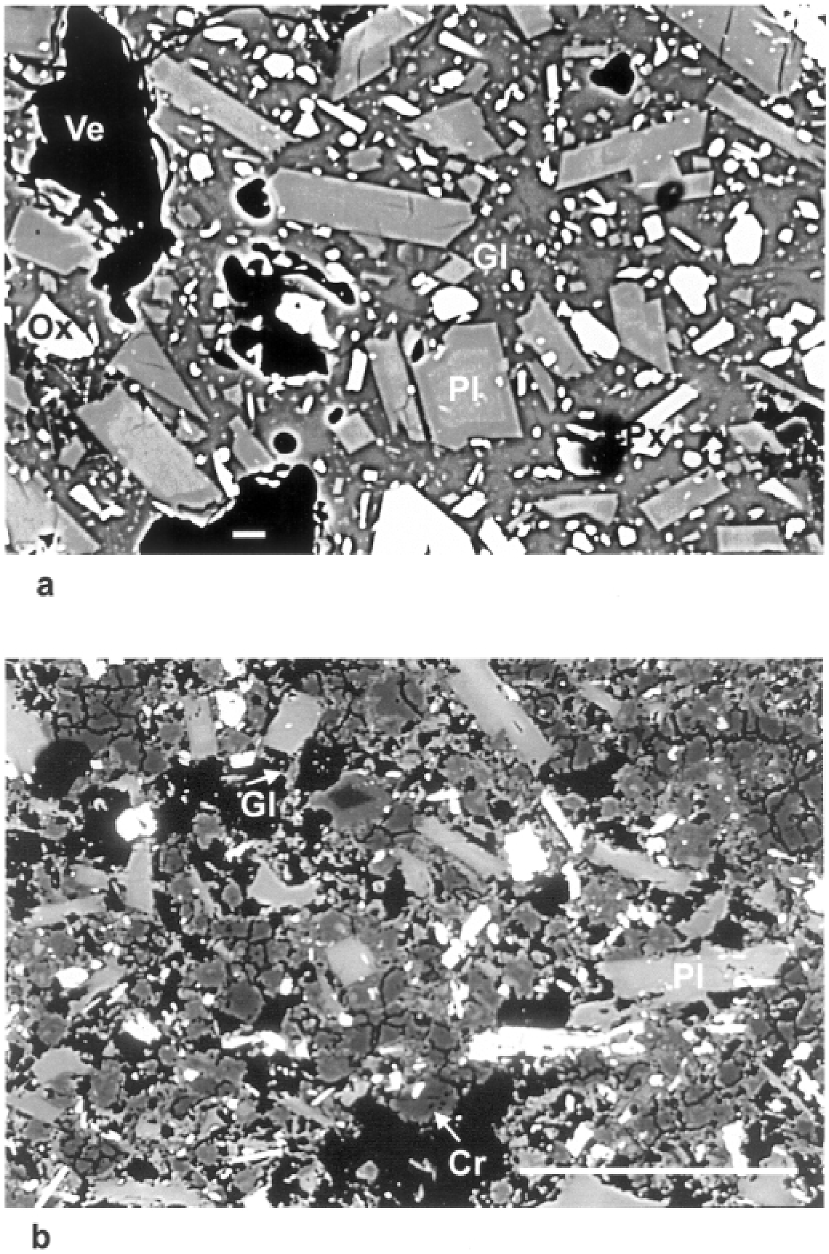


Fig. 1 Backscattered electron micrograph images of the groundmass lava of Soufriere Hills Volcano, Montserrat. (a) Lava block from pyroclastic flow (August 1996) following rapid period of dome growth. Microlites and microphenocrysts of feldspar (Pl) and oxide (Ox) are set in a rhyolite glass (Gl), seen as the grey continuous phase containing vesicles (Ve). The smallest-scale speckles in the glass are sections across tiny microlite needles. White scale-bar is 10 μm. (b) Lava block from pyroclastic flow, illustrating typical texture of dome material after prolonged residence within the dome. Coarser microlites of feldspar (Pl) and oxide are set in a finer mixture of feldspar, cristobalite (seen as numerous tiny dark blebs and marked Cr) and residual glass (Gl). White scale-bar is 100 μm.

in vesicles (Fig. 1b; Baxter *et al.*, 1999). Hornblende, from dome samples which have resided for more than a few days in the dome, is typically blackened by oxidation and sometimes shows reaction rims consistent with slow magma ascent rates (Devine *et al.*, 1998).

Major episodes of dome collapse excavate material originating deep within the dome. For example, on 17 September 1996, 40% of the dome collapsed over a 9-h period, removing about 11.7×10^6 m^3 of lava from a dome with a precollapse volume 29×10^6 m^3 (Robertson *et al.*, 1998). The interior of the dome represented by the collapse scar was exposed to a depth of 210 m. The pyroclastic flow deposits of the 17 September 1996 eruption consist of dense juvenile blocks derived from the dome, with a highly crystalline groundmass and low proportions (< 15 vol%) of high-silica rhyolite interstitial glass, and contain oxidized hornblende. Predominantly the blocks represent the interior of the dome that had grown over the preceding few months (Sparks *et al.*, 1998). Similarly many of the other major dome collapses in the eruption have sampled deep (> 100 m) into the dome and generated clasts with predominantly highly crystalline groundmasses.

All of these observations indicate that significant groundmass crystallization occurred both as the magma ascended and within the dome.

Observations of dome growth

The Soufriere Hills dome is classified morphologically in the spiny to lobate category of Fink and Griffiths (1998). The morphology varies from large individual spines (Fig. 2), to a blocky conical structure with many spiny protrusions (Fig. 3a,b) to smoother lobes (Fig. 3a,c). Spines consist of tall pinnacles (Fig. 2) and extrude in a few days with dimensions up to 60 m tall and 30–50 m wide. Lobes are larger scale structures, which extrude asymmetrically (Fig. 4). Spines and lobes extrude along smooth curving surfaces (Fig. 3b,c), with striations in the movement. Fault breccias are also observed along these surfaces, which are interpreted as shear zones moving in stick-slip fashion. Shear zones with large surface areas (10^4 m^2 scale) control the extrusion of lobes at displacement rates of 20–30 m day^{-1} (Fig. 3). Few samples of the Montserrat lava show flow foliation in the groundmass. However, samples with well-developed foliations and fragmented phenocrysts are found in explosive ejecta (Robertson *et al.*, 1998). These samples are similar to cataclasites at the margins of large spines in the Mount Unzen dome, Japan. They are interpreted as samples from shear zones deep within the dome and conduit. The shear zones for the

Fig. 2 Large spine of lava extruded over a 2-day period in April 1996. The spine is about 60 m high and shows two kinds of surface. On the left side of the spine a smooth striated curving surface is observed formed by shear along a fault originating in the conduit. On the right side of the spine there is a steep broken face with a talus of rock-fall debris at its base.

tallization of the Mount St. Helens dacite during decompression and illustrated the large amounts of crystallization caused by decreasing water pressure. Their experiments on similar compositions to the rhyolitic melts on Montserrat indicate undercoolings of about 150–200°C as a consequence of degassing a rhyolitic melt with 4% water. Exolution of gas causes the melt viscosity to increase by several orders of magnitude (Dingwell *et al.*, 1996). Crystallization results in very large changes in viscosity when a threshold crystal content is reached and crystals start to form a touching framework (Marsh, 1981; Lejeune and Richet, 1995). Further crystallization beyond this threshold also can cause the magma to develop strongly non-Newtonian properties and mechanical strength. Highly crystalline magma can deform heterogeneously and can fail as a brittle solid.

The rheological properties of the degassed dome can be constrained by both experimental studies and observations. First, we have carried out series of uniaxial creep experiments on highly crystallized ($<$ 10 vol% melt) samples of Soufriere Hills lava at constant load pressures ranging from 7 to 28 MPa and at temperatures varying between 940 and 1030°C. All the samples display the same behaviour when subjected to a constant compressive stress (example shown Fig. 6). In the initial stage of the creep tests, the strain rate is constant and the deformation regular. Viscosities in the range 10^{13}–10^{14} Pa s were measured at 993°C. Then the strain rate accelerates rapidly as samples undergo extensive microfracturing, leading eventually to the sample failure in a way which has been extensively described in the literature (e.g. Paterson, 1978). Just prior to failure the apparent viscosity reduces to values of only 10^{11} Pa s with deformation localized along shear zones of microfractures which amalgamate into a shear surface at failure. Secondly, the velocity, V, of extrusion of lobes along shear zones in the dome is typically in the range 20–30 m day^{-1}. If the width of the shear zone, x, is typically a metre then the strain rate is V/x and an apparent viscosity can be calculated if the shear stress is known. We estimate a shear stress of around 5 MPa based on the dome height and estimates of overpressures in the explosive eruptions (Melnik and Sparks, 1999). These estimates indicate that the viscosity of the shear zones is about

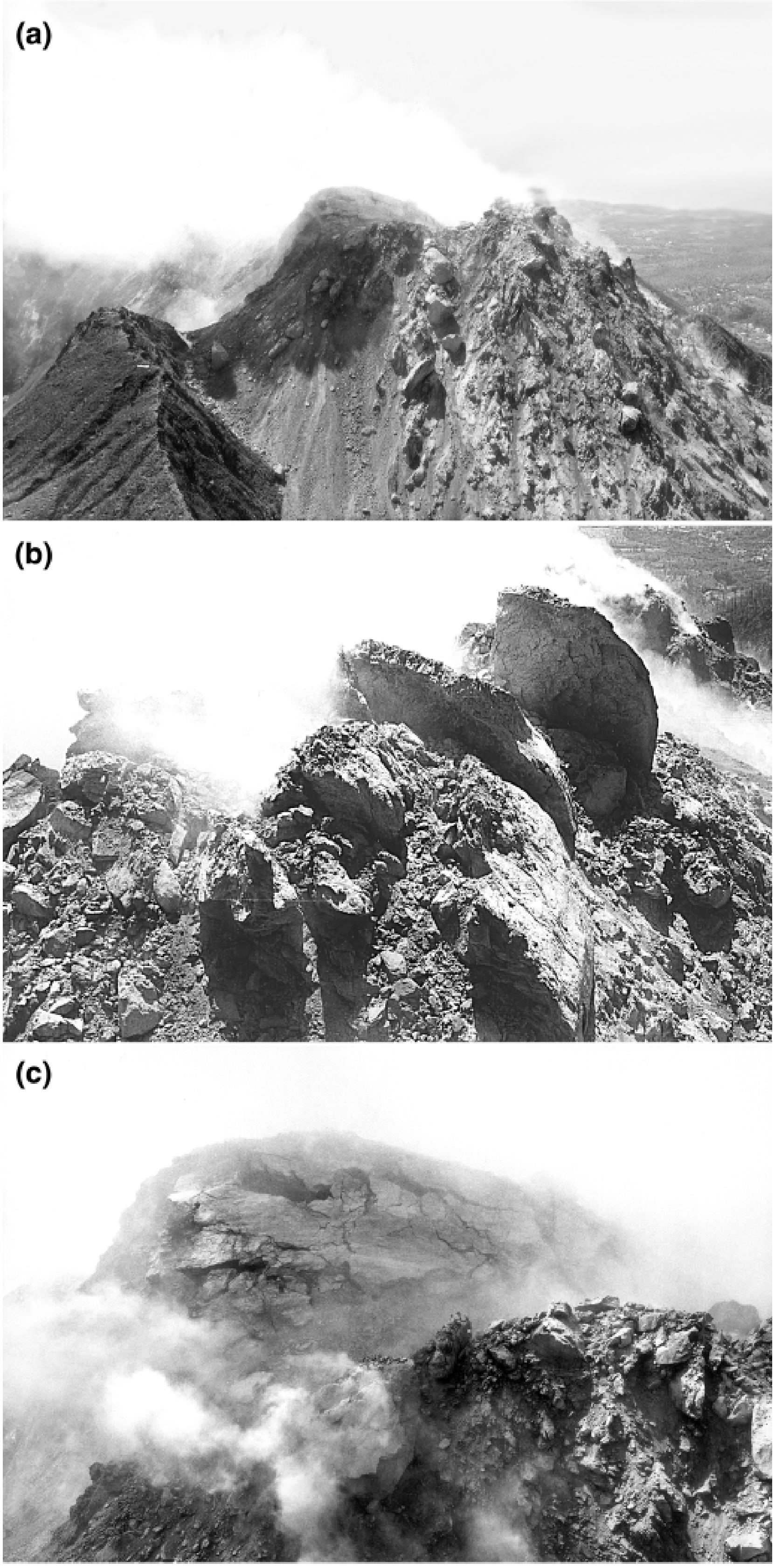
spines and lobes were located over the vent area throughout the eruption and they are interpreted as originating at the wall of the conduit (Fig. 4).

We have observed many large fractures in the dome interior exposed immediately after a major collapse (Fig. 5). We have also observed fractures (10–200-m long) opening on the dome surface and generating jets of gas and ash from the interior. Gas emission through fractures can be correlated with long period earthquakes (Miller *et al.*, 1998), which are interpreted to be the result of resonance from flow of high pressure gases along the fractures (Chouet, 1996). Similar phenomena have been reported in the andesite dome of Galeras, Colombia (Gil Cruz and Chouet, 1997), and the dacite dome of Mount St Helens (Mastin, 1994) Most earthquakes at the Soufriere Hills are shallow ($<$ 2 km) and are described as hybrids with long-and short-period components (Miller *et al.*, 1998). Hybrid events are interpreted as hydrofracturing of the magma within the overpressurized upper conduit (Sparks, 1997; Melnik and Sparks, 1999; Voight *et al.*, 1999). The formation of large fractures and the occurrence of seismicity within the interior of domes and in the conduit requires the magma to be sufficiently crystalline to switch between brittle and ductile behaviour, presumably dependent on rates of strain induced by gas pressurization and build-up of stress.

These observations indicate that the magma in deep parts of the dome and the shallow conduit is substantially crystallized so that the lava behaves like a partially molten crystalline solid with strength rather than a Newtonian fluid, with much of the deformation focused by localized shear and brittle fracture development.

Rheological changes caused by degassing and crystallization

Using the petrological estimates of magma properties in the magma chamber (Murphy *et al.* 2000) the initial viscosity of the magma is estimated at 7×10^6 Pa s using experimental data on the effects of water and suspended crystals on viscosity (Lejeune and Richet, 1995; Dingwell *et al.*, 1996; Richet *et al.*, 1996). As decompressing magma exsolves gas at near-surface pressures, the liquidus of the melt phase increases, resulting in strong undercooling, triggering crystallization and inducing rheological stiffening of the magma. The experiments of Geschwind and Rutherford (1995) investigated the crys-



10^{10}–10^{11} Pa s. The height of the spines (up to 60 m) also implies a minimum shear strength of about 1 MPa (Voight *et al.*, 1999)

The influence of cooling

Lava dome morphologies are often related to the formation of a surface-cooled crust (e.g. Fink and Griffiths, 1998). However, cooling cannot have played an important role in the high degree of crystallization observed in samples originating from within the conduit and the dome interior. A thermal wave from external cooling penetrates a characteristic distance, l, in a time given as l^2/κ, where κ is the thermal diffusivity. Thus in a month ($\kappa = 7 \times 10^{-7}$ m^2 s^{-1}) the 'crust' would be about 2 m thick, less than the characteristic block size on the lava surface. Over a year, conductive cooling would only penetrate 5 m. Although rainfall and the fragmented nature of the surface (Fig. 2) may enhance cooling rates, these will be second-order effects. For example, an annual rainfall of 1 m raised to 100°C can cool lava to an equivalent depth of 2.5 m. On Montserrat slow conductive cooling can be demonstrated by observations of lava erupted in July 1996, which subsequently stagnated and was reactivated in April 1997. Avalanches, which removed only a few metres of surface material, revealed a strongly incandescent interior (> 650°C),

Fig. 3 (Left) In April 1997 a large lobe of lava extruded on the south-west side of the dome on a curved NW–SE orientated shear zone. (a) The lava dome viewed from the south-coast on the 3 April 1997. The right-hand peak extruded in February and March 1997 and shows a typical conical shape, spiny summit (see b) and blocky surface. The left-hand smooth lobe was the active area extruding from right to left along a ductile shear fault (see c) at a velocity of 25–30 m day^{-1}. Note the gas plume emerging from conduit in the gap between the lobe and conical peak. (b) Spiny summit of the right-hand conical peak, showing slab-like spines (10–15 m high and 2–4 m wide) and smoothed surfaces. (c) The active lobe of 3 April shows surface striations related to extrusion from ductile shear zone located to the right.

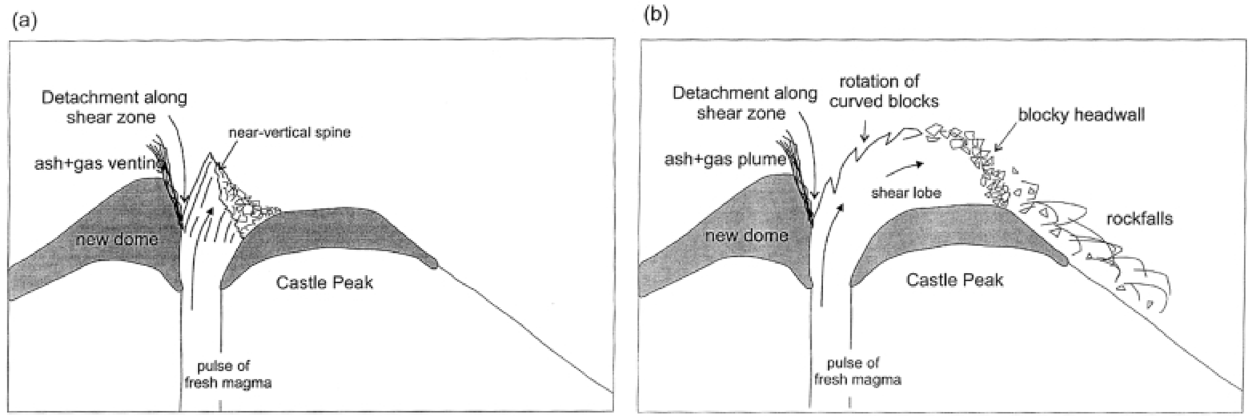


Fig. 4 Schematic diagram showing the interpreted mechanism of spine formation (a) and shear lobe development (b) during the growth of the Soufriere Hills andesite dome, Montserrat. Large curving shear surfaces develop by detachment at the conduit wall. For low extrusion rates and highly crystalline and mechanically strong magma, spines form up to 60 m high (a) and then topple over. For larger extrusion rates and more ductile (and probably less crystalline) magma the lava extrudes as an asymmetric lobe bounded by a shear surface originating along part of the conduit wall (b). The lobe advances and breaks up to form a blocky surface, and breaks up at the flow front to form rock-falls and pyroclastic flows.

Fig. 5 The interior of the dome is exposed after a major collapse of the dome on 17 September 1996 revealing that its interior is heavily fractured. The photograph was taken of the head-wall of the collapse scar 8 days after the collapse and shows about 70 m depth. Large fractures at least 50 m in length can be seen.

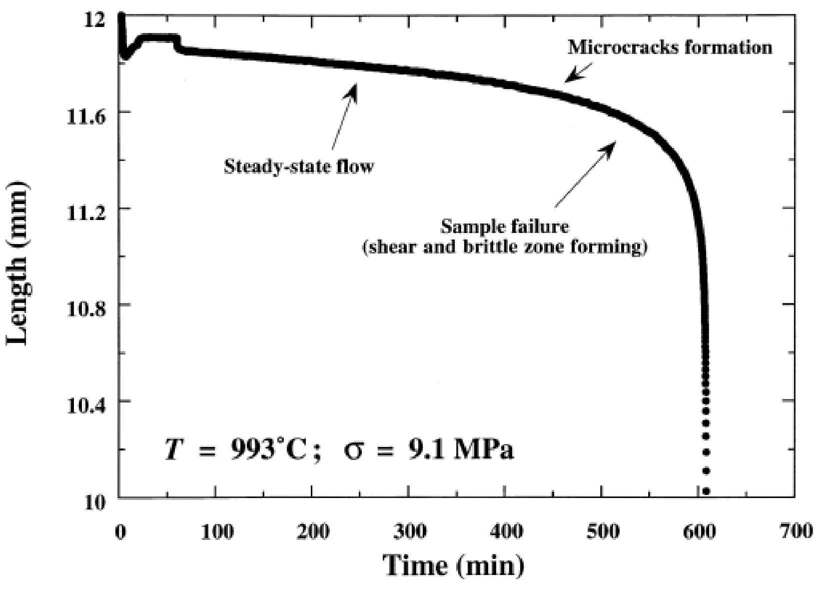


Fig. 6 Deformation curve of a sample of the Soufriere Hills andesite subjected to a uniaxial compression (9.1 MPa load pressure). The experiment has been performed at room pressure and at 993°C on lava dome material erupted in January 1996. The plot shows the length of a cylindrical core of lava as a function of time (the initial sample length was 12 mm for a 4.8-mm diameter). Initially the sample deforms in a regular manner at a constant strain rate with a viscosity of about 10^{14} Pa s. After a few hours, sample deformation accelerates and the apparent viscosity decreases substantially with an estimated value of 10^{11} Pa s just before failure. The increasing strain rate results from a rising rate of formation of microcracks. Failure takes place along a shear surface, which develops from a zone of microfractures.

showing that the interior remained hot for several months.

Discussion

Emplacement of the Soufriere Hills andesite dome does not prescribe an important role for surface cooling. The magma solidifies as a consequence of degassing during decompression. This process initiates at depth in the conduit and is thus much more pervasive than the effects of surface cooling. Highly crystalline lava cannot easily spread sideways. New lava coming into the dome pushes out spines and lobes at the dome summit, which eventually become unstable and generate pyroclastic flows. The curving striated shear zones that bound the spines and lobes are interpreted to originate as detachment surfaces along the conduit walls (Fig. 4).

In eruptions such as the Soufriere Hills the magma can become highly crystalline within the conduit. This rheological stiffening can cause several phenomena, such as shallow seismicity, shallow zones of overpressure development with accompanying ground deformation, and cyclic patterns of dome extrusion, perhaps related to stick-slip mechanisms (Sparks, 1997; Denlinger and Hoblitt, 1999; Melnik and Sparks, 1999; Voight *et al.*, 1999).

The concepts developed here can be used to explain the contrasts in morphology between some andesite and rhyolite lavas. Large spines, lobes of lava guided along shear zones, and steep-sided domes occur most commonly in porphyritic lavas of andesitic composition, and are typically associated with pyroclastic flows formed by gravitational collapse. In contrast many high-silica rhyolite lavas are much more glassy and can form coulées and relatively thin extensive lava flows (Fink, 1983; Westrich *et al.*, 1988). They are not commonly associated with collapse-generated pyroclastic flows. Internal textural zonation and surface structures of rhyolite flows can be interpreted as being influenced by external cooling.

These differences between some rhyolite lavas and the less silicic lavas can be related principally to crystallization kinetics and the relationship of magma crystal content to rheological transitions. When crystal content approaches the percolation threshold and crystals begin to come into contact to form clusters (Marsh, 1981; Pinkerton and Stevenson, 1992; Lejeune and Richet, 1995), large increases in viscosity, non-Newtonian behaviour and strength develop with small amounts of further crystallization. At the same time crystallization kinetics become increasingly sluggish as residual melts exsolve gas and become more silica rich. We suggest that the morphology of lavas strongly depends on when and where the crystal content threshold is reached during magma ascent and lava emplacement. In the case of a crystal-poor high-silica rhyolite magma, gas is lost during ascent, but sluggish crystallization kinetics allow magma to extrude and then to flow for long periods of time as a metastable undercooled melt and to be preserved as glass. Textural evidence (Westrich *et al.*, 1988) implies that much crystallization in rhyolitic lavas is delayed until long after emplacement. Thus the rheological transition is not reached on the timescale of extrusion and formation of a cooled crust is the main influence on emplacement. In contrast, the Soufriere Hills andesite was already a phenocryst-rich magma close to the rheological transition, and the conditions during ascent were such that groundmass crystallization could take place as the magma ascended and exsolved gas. Consequently the rheological transition was reached within the conduit so that the magma extruded as a hot crystalline solid with small amounts of residual melt.

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