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RESEARCH ARTICLE

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Rapid dome growth at Montagne Pelée during the early stages of the 1902–1905 eruption: a reconstruction from Lacroix's data

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Abstract Information obtained from various parts of the two books on Montagne Pelée by Lacroix enables an estimate to be made of the size of l'Etang Sec summit crater, the volume of the 1902–1905 lava dome and its growth rate at various stages of development. During the week preceding the 8 May nuée ardente, dome growth was between 28 and 38 $m^3 s^{-1}$, leading to a volume of 17–23×10^6 m^3 on the morning of the catastrophe. Considering that significant parts of the dome (~1/3?) were removed by the 8 and 20 May climactic eruptions, a high magmatic flux could have continued until at least 27 May, when the total remaining volume was estimated to 53×10^6 m^3. After moderate activity in June–July (of order 10 $m^3 s^{-1}$), vigorous dome growth resumed dramatically, leading to the third climactic eruption of 30 August (a true calculation for this period being not feasible because of poor quality of the data). From November 1902 to July 1903 most of the effusive activity was concentrated in the great spine (erupted volume ~15×10^6 m^3, magma flux 1.2 $m^3 s^{-1}$), which was eventually destroyed by collapse and minor nuées ardentes. The end of the eruption was characterized by a very low effusion rate, <1 $m^3 s^{-1}$ in average from August 1903 to October 1905.

Keywords Density current · Explosive volcanism · Lava dome · Mt. Pelée · Subduction zone

Introduction

It may be questioned whether explosivity of lava domes can be linked to their growth rate, that is their effusion rate. Rapid dome growth is expected to increase the potential for hazardous explosive activity such as nuées ardentes in at least three ways: (1) it leads to exsolution of larger amounts of gas, (2) prevents their loss through the conduit walls, and (3) enhances dome instability by gravitational collapse (e.g. Jaupart and Allègre 1991; Sparks 1997). At Montagne Pelée in 1902, despite thorough measurements performed towards the middle and late stages of the eruption (Lacroix 1904, 1908), there are very few data available for the most exciting early period that gave way to the destructive nuées ardentes of 8 and 20–26 May, 6 June, 9 July and 30 August. The purpose of this note is to gather these data and to show that a significant lava dome developed at a fast rate during early May, thus providing more information on a possible mechanism for the production of the so called pelean style of eruption.

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The shape and size of l'Etang Sec summit crater prior to 1902

The paramount importance in reconstructing the topography of l'Etang Sec summit crater (or caldera) prior to the 1902 eruption was envisaged by Alfred Lacroix who discussed, in detail, the data at his disposal (Lacroix 1904, pp. 19–21). According to the few people (e.g. Father Vanhaecke) who survived the volcano catastrophe and who had a wide acquaintance with the mountain before 1902, l'Etang Sec ("the dry pond") had the shape of an inverted colonial hard hat, whose upper diameter varied following different estimates from 700 to 1,500 m. In fact, l'Etang Sec caldera was actually measured at the end of the eruption, and a true map is given in Lacroix's poorly known book "La Montagne Pelée après ses éruptions" (1908, p. 10). Following this map (Fig. 1), the crater was slightly elongated in the NNE–SSW direction with a maximum diameter of 1,150 m. Its smaller, WNW–ESE axis was 900 m. Although the crater might have been enlarged by a few meters or tens of metres through collapse of its inner walls with respect to its former size, these measurements are indisputable elements for calculating the volume of the lava dome at the end of the

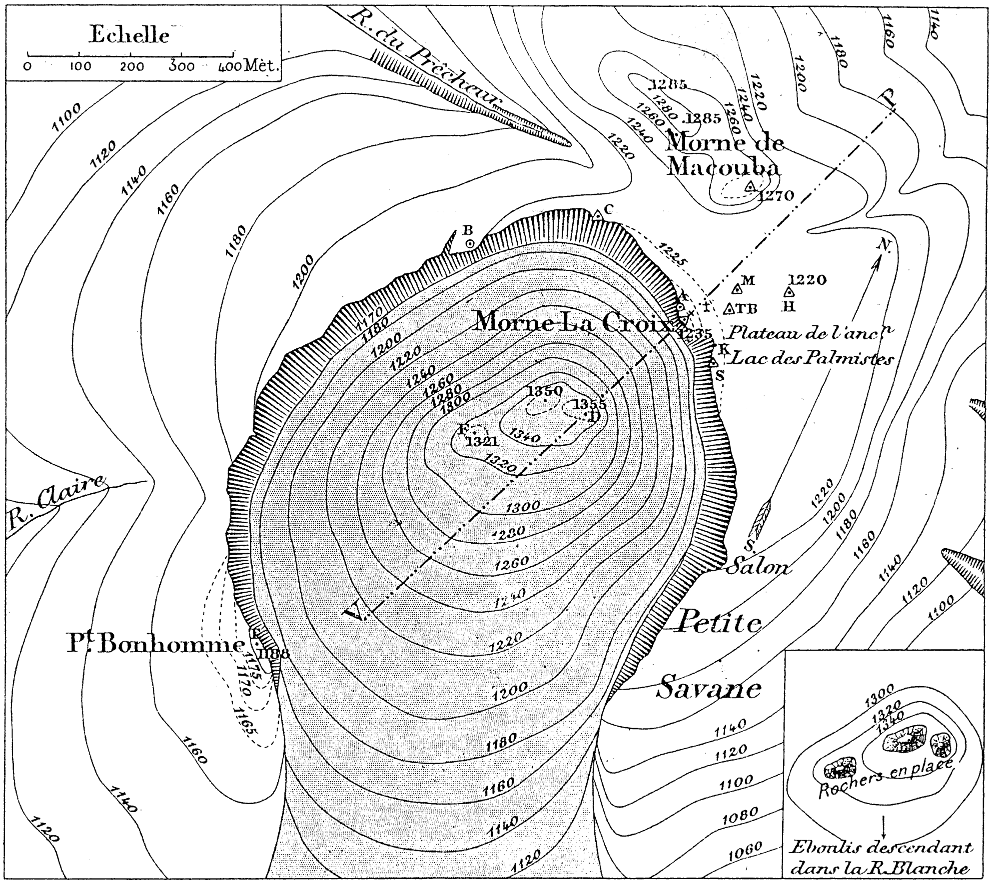

Fig. 1 Map of the summit crater of l'Etang Sec and dome at Montagne Pelée in January 1905 (Lacroix 1908)

eruption, provided that the shape and elevation of the crater floor are known.

In his first main book, Lacroix (1904, p. 21) made various attempts for determining the crater floor elevation. He finally concluded it was "close to 1,000 m" above sea level (a.s.l.). However, his discussion with respect to this particular point is sometimes misleading. For example, he suggests there is a large uncertainty, between 921 and 1,077 m a.s.l., for the crater floor elevation, although he had given 921–994 m a few lines before, 994 being another evident error for 943 (see note 1 at the bottom of his p. 21). Furthermore, he measured 1,010 m on 15 July 1902 for the lowest part of the growing dome visible through the southern rim of the crater, which certainly could not be lower than the bottom.

Most of these doubts seem linked to those regarding the altitude of the summit of Montagne Pelée, from which estimates of the crater depth were made. The summit was represented by Morne La Croix, an old andesitic mound towering 50 to 60 m above the highest NE rim of l'Etang Sec (Eugène Berté, in Ariès et al. 1981; Father Vanhaecke, in Chrétien 1983). This NE rim reaches a maximum of 1,225 m and, therefore, the figure of 1,351 m a.s.l. assumed at the time for Morne La Croix, which resulted from measurements made in 1815, appears in excess by more than 65 m (see also Tanguy 1994, p. 90).

In fact, barometric readings carried out by Le Prieur et al. (1852) gave an elevation of 1,277 m for Morne La Croix. This value is exactly the same as that resulting from topographic measurements performed on 22 May 1902 by officers aboard the ship *Le Tage* (Lacroix 1904, p. 79). The value of 1,277 m is also said by Heilprin (1903, p. 169) to be consistent with his own barometric observations during an ascent to the summit at the end of May. Such considerations raise the question of whether or not Morne La Croix did collapse on 8 May, as commonly believed. Lacroix further indicates (1903, p. 55, 1904, pp. 79, 121) an altitude of 1,270 m on 29 June and 1,230 m on 4 October 1902. Although this does not preclude earlier crumbling, it brings substantial evidence for a rather complex collapse occurring at different times.

In 1851, while determining 1,277 m at Morne La Croix, Le Prieur estimated the crater depth to be "less than 400 m" ("300 m" according to Father Vanhaecke, also quoted by Lacroix). These figures give 877 and 977 m for the crater bottom, respectively, not 1,077. Moreover, just after having climbed the mountain, Le Prieur descended inside the crater to a small lake whose elevation was found to be 921 m a.s.l. This is the only true measurement available for the bottom of l'Etang Sec, and it appears quite accurate with respect to the other estimates. The crater floor, of course, was not everywhere at the same elevation, and appeared as gently inclined towards St. Pierre, that is, from the north to the south. It is likely that the crater floor went from a maximum of about 950 m a.s.l. below the inner wall of Morne La Croix to about 900 m near the southern rim. In the following calculations I have used the figure of 925 m a.s.l. as the mean elevation of the crater floor.

Volume of the lava dome at the end of the eruption (1905)

The map published by Lacroix resulted from measurements carried out by officers of the French army in January 1905, that is a few months before the end of the eruption taken as on 4 July 1905 for explosive phenomena, and on 30 October of the same year for incandescence of the dome (Lacroix 1908, p. 5). It is likely that, therefore, only a small increase in the volume of the lava dome took place after the map was finished. Surprisingly, Lacroix did not take advantage of this document when making an attempt of volume estimate. He probably believed that the rough approximation of "over 100 millions of cubic meters" for the dome claimed in his main work (1904, p. 132) was sufficient information.

Examination of the map (Fig. 1) shows that the lava dome had filled the crater to the almost uniform altitude of 1,170 m. The shape of the dome is rather conical with slopes going from 40–50° on the north-east side to only 15° on the south. This asymmetry probably comes from the fact that the crater was open to the south and that lava accumulated there and partly flowed or crumbled into the deep Rivière Blanche valley. If one does not take into account this latter complication, the part of the dome within the crater itself and above 1,170 m a.s.l. has practically the shape of a cone with an average diameter of 950 m (475 m radius) and a height of 1,355–1,170=185 m (Fig. 2). The resulting volume of 44×10^6 m^3 represents only that of the upper part of the dome.

In order to respect the shape of the crater indicated by former observers, I extrapolated the mean slope of its inner walls above 1,170 m, as given by the map (50°), to the arbitrary elevation of 1,000 m a.s.l., and obtained, at this level, an approximate radius of 330 m. This is consistent with the features of numerous photographs that

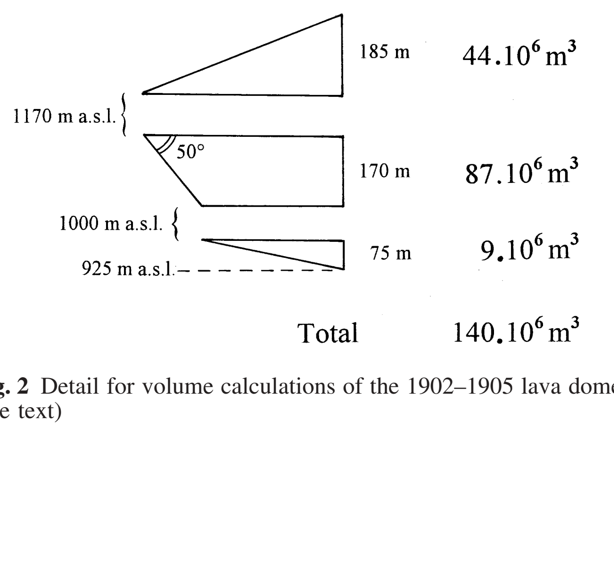

Fig. 2 Detail for volume calculations of the 1902–1905 lava dome (see text)

consistently show very steep slopes for the caldera walls. It also roughly agrees with pre-eruption estimates of between 300 and 600 m for the diameter of the bottom (or that of the lake?). The volume thus obtained is that of an inverted truncated cone that is 170 m high, with an upper radius of 475 m and a lower radius of 332 m (Fig. 2), resulting in another 87×10^6 m^3.

The lowest part of the crater, which occasionally contained a lake, has been assumed to be an inverted cone with a radius of 330 m and a height of 75 m (i.e. between 1,000 and 925 m a.s.l.). This adds a further volume of 9×10^6 m^3 to the erupted lava.

In conclusion, the lava dome built within l'Etang Sec crater in 1902–1905 reached a volume of 140×10^6 m^3, with a probable error of no more than ±20%. This figure does not take into account the amount of lava lost into the deep Rivière Blanche valley, nor that of material removed from the dome by explosive phenomena.

Volume of lava emitted during the early stages of the eruption

The shape and size of the crater defined above allows an estimate of the volume of lava produced during the early stages of the eruption by using Lacroix's information on the dome height at various times of its growth. For this purpose, I assumed for the growing dome a conical shape with an average slope of 35°, which fairly corresponds to the actual shape of viscous lava domes during early stages of their growth (Fig. 3a, b; see also Huppert et al. 1982, p. 209). Figure 3b shows that the Pelée dome had a slope close to 35° even after the great spine had begun to grow.

Evidence for a substantial lava dome before the 8 May 1902 eruption

The accounts of several people led Lacroix (1904, pp. 110–112) to consider that, as early as 7 May, a large accumulation of high-temperature material had a sufficient height to be seen from Saint-Pierre, and that because incandescent blocks rolled down and climbed against the opposite crater wall of Petit Bonhomme (1,188 m a.s.l. at the time), "the dome should had reached an altitude well close to 1,200 m". By means of the method explained above, a volume of 23×10^6 m^3 is obtained (Fig. 4a). Even when admitting a flat bottom of the crater at 1,000 m elevation (and this is unlikely), one must accept a minimum of 17×10^6 m^3 of lava.

Magma probably began to invade the bottom of l'Etang Sec on 30 April, on the evening when a crater glow was reported for the first time (Brother Gérard, in Chrétien and Brousse 1988, p. 94, see also Tanguy 1994, pp. 93–94). During the night of 2 to 3 May, several witnesses indicate incandescence or "flaming vapors" at the base of the ash column, and "luminous rockets", which are evidently jets of magmatic material. On the evening of 3 May, "balls of fire exploding with tremendous noise"

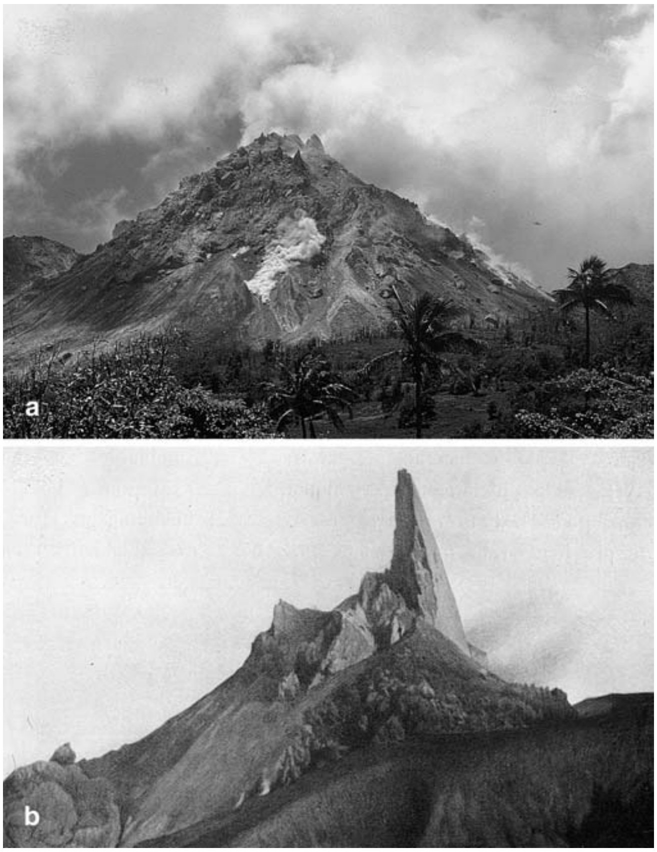

Fig. 3 a Cone-shaped dome of Soufrière Hills volcano, Montserrat, at an early stage of development (March 1997, photograph by J.C. Tanguy). **b** Dome and spine of Montagne Pelée in March 1903 (Lacroix 1904)

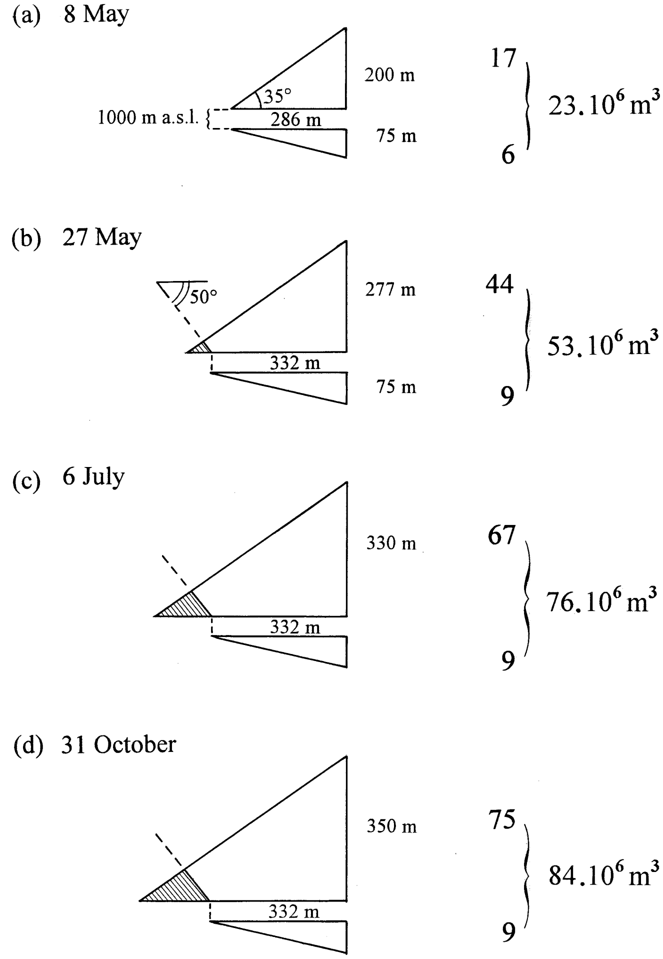

Fig. 4 Reconstruction of dome growth from Lacroix's data during early stages of the 1902 eruption: **a** 8 May; **b** 27 May; **c** 6 July; **d** 31 October

were noticed from the ship *Saint-Germain* in the harbour of Saint-Pierre. Finally, the 5 May lahar that destroyed the Guérin factory might have been caused by a small pyroclastic flow, as suggested by Lacroix (1904, pp. 172–175, 180). This is further evidence for magma inside the crater at this date.

By assuming that the lava dome began to grow on the evening of 30 April, effusion rates of 28 to 38 m^3 s^{-1} can be estimated for the week preceding the evening of 7 May. Although quite high, this figure is of the same order of magnitude as those quoted at Mt. Redoubt in 1989 (Miller 1994) or at Mt. St. Helens cryptodome in 1980, taking into account that this later composed the whole of the 0.2 km^3 of juvenile materials estimated in the 18 May deposits (Christiansen and Peterson 1981).

The dome from May to October 1902

On 27 May, the top of the lava dome was seen "higher than the crest of the mountain" (Lacroix 1904, p. 112) by sailors of the *Tage* who had measured an elevation of 1,277 m a few days earlier for the Morne La Croix (see above). By assuming the minimum value of 277 m for the height of the cone-shaped dome, and taking into account the effect of the inner crater wall, a figure of 44×10^6 m^3 is obtained (Fig. 4b). In addition to the 9×10^6 m^3 from the bottom between 1,000 and 925 m a.s.l., this value gives to the whole lava dome a total of 53×10^6 m^3. This indicates a growth rate of 17 m^3 s^{-1} since 8 May, which is lower than that estimated at the beginning of the eruption. However, parts of the dome were probably destroyed by the powerful blasts of 8 and 20 May. If materials removed are assumed to represent about a third of the dome at the time of each eruption, then 15 million m^3 (i.e. 23–8) existed after 8 May, and 38 million m^3 (53–15) grew afterward. To this number can be added the amount lost on 20 May, i.e. $38\times1/3\approx13\times10^6$ m^3. So that (53–23)+8+13=51 million m^3 were actually erupted between 8 and 27 May, leading to about 30 m^3 s^{-1}. This is almost the same eruption rate as before 8 May.

On 6 July, Officer Deville, measured from Saint-Pierre, an altitude of 1,353 m for a small spine emerging from the clouds that concealed the remainder of the dome (Lacroix 1904, p. 114). Experience gained from the ongoing eruption at Montserrat shows that small spines are usually overtopping the true summit of the dome by no more than 20–30 m (P. Dunkley, personal communication, May 2002). Using for Montagne Pelée a corrected elevation of 1,330 m on 6 July 1902, the dome had probably reached, at that time, a volume of 76×10^{6} m^{3} (Fig. 4c), indicating a rather low effusion rate after 27 May (or 6 June?). Considering the period between 27 May and 6 July, the dome volume increase was 23 million m^{3} (76–53), augmented by perhaps 15 million m^{3} lost in the moderate eruption of 6 June, therefore giving (76–53)+15=38 million m^{3} erupted, and an average extrusion rate of ~11 m^{3} s^{-1}. However, considering the uncertainty of the actual volume lost on 6 June, it may be better to simply suggest that the extrusion rate was in the order of 10 m^{3} s^{-1}.

Although many witnesses saw considerable dome growth before the 30 August eruption, an increase in height of 100–150 m indicated in a police report (Lacroix 1904, p. 115) for the period 15–27 August appears largely exaggerated. These estimates are too imprecise, therefore, to allow a proper calculation. On the other hand, a large part of the summit dome was probably destroyed on 30 August. The first regular measurements beginning in October indicate an elevation for the dome of between 1,300 and 1,380 m, with most measurements being close to 1,350 m (Lacroix 1904, p. 130). Calculations that take into account this figure of 1,350 m as the mean elevation of the summit on 31 October lead to a volume of 84×10^{6} m^{3} (Fig. 4d).

The great spine: November 1902 to August 1903

The great spine emerged from the dome during the night of 3 to 4 November 1902. Its growth was accompanied by numerous, though less violent nuées ardentes, which were confined within the Rivière Blanche valley. Despite continuous loss of mass owing to explosive eruptions from its base and crumbling of its walls during ascent, the spine rapidly reached an elevation of 1,575 m a.s.l. (24 November, sketch in Lacroix 1904, p. 124). Further alternate crumbling and growth eventually resulted in a maximum height of 1,617 m on 31 May 1903, but on 10 August this stupendous structure was completely shattered. On the basis of Lacroix's precise measurements performed almost every day, this stage of the eruption was re-examined by Jaupart and Allègre (1991) who concluded that the eruption rate was unsteady and occurred in pulses triggering both increasing dome growth and collapsing nuées ardentes. A similar behaviour is likely for earlier stages (May and August 1902), as it appears from the preceding section. The abrupt changes in flux rates recall the cyclic behaviour observed at Montserrat (Voight et al. 1999).

On 10 August 1903, the dome had reached an average height of 1,365 m a.s.l. (Lacroix 1904, p. 128), corresponding to a volume of about 100×10^{6} m^{3}. Although the dome at that time was rather enlarged and no longer conical, this suggests that most of the lava output since November 1902 was concentrated in the great spine. Lacroix estimated that if the spine had not suffered loss of mass during its entire development, then it would have reached 2,200 m a.s.l., representing a cylinder 850 m in height and 150 m in diameter. This implies that at least 15×10^{6} m^{3} of lava was extruded in this way between November 1902 and July 1903 (1.2 m^{3} s^{-1}).

The end of the eruption (1903–1905)

Subsequent growth of the dome occurred mainly towards Morne La Croix against the NE inner wall of the crater (photographs in Lacroix 1908, pp. 2–3), increasing its volume to about 140×10^{6} m^{3} in January 1905 (section 3). An average effusion rate of 0.9 m^{3} s^{-1} is thus obtained for the period commencing August 1903. However, it is likely that the dome growth decreased towards the end of the eruption. The last, weak pulse of activity occurred in June–July 1905 and very probably did not increase the volume of the dome by more than a few million cubic metres.

Discussion

These data further substantiate the view that explosive phenomena in lava domes are closely linked to their growth rate, or effusion rate (Fig. 5). Although it was formerly stated that, in a majority of cases, explosivity shows no systematic relationship to the average rate of dome growth (Newhall and Melson 1983), other authors have emphasized that dome growth may be quite variable during the same eruption and is usually larger at the beginning (Huppert et al. 1982; Miller 1994; Nakada et al. 1999). These later authors observed that major explosions or pyroclastic flows took place when the lava effusion rate was high. Conversely, the ongoing eruption at Montserrat provided a case where dome growth is low at the beginning and increases with time though remaining at relatively low levels (≤6 m^{3} s^{-1}), and no violent ex-

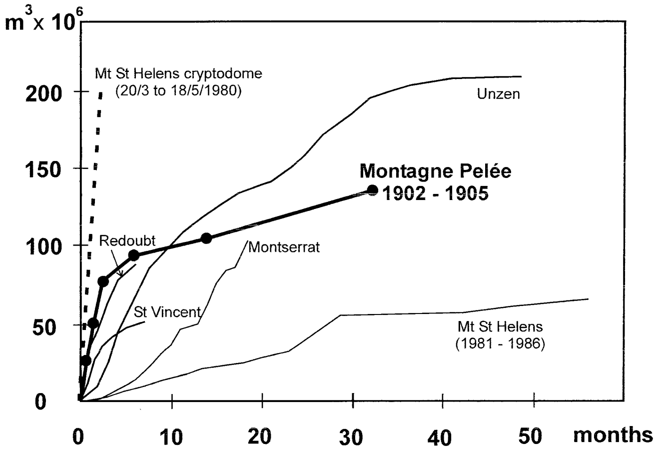

Fig. 5 Various types of lava dome growth, completed after Nakada et al. 1999

plosion occurred within 10 months of the dome appearance (Young et al. 1997; Druitt and Kokelaar 2002). Similarly, the waning phase of the Mt. St. Helens eruption was characterized by low extrusion rate and weak explosive activity (Swanson and Holcomb 1991). However, high magma supply (~40 $m^3 s^{-1}$) was reached before the catastrophic 18 May 1980 eruption, if one assumes that the cryptodome began to grow at the beginning of seismic activity on 20 March, and that all fresh material erupted on 18 May belongs to the dome (Christiansen and Peterson 1981). At Montserrat, although the magma flux was low at the start, the major activity occurred when flux was relatively high, with 7-week cycles heralded by even higher flux rates (Voight et al. 1999).

It must be clear, also, that the magma volatile content plays a dominant role in the explosivity of all eruptions, including dome-building eruptions (e.g. Sparks 1997; Scandone and Giacomelli 2001). At St. Vincent in 1971, no explosion occurred during the development of an $80\times10^6 m^3$ dome within a crater lake, despite a relatively high initial effusion rate (11 $m^3 s^{-1}$, Aspinall et al. 1972). However, as the initial effusion took place beneath the crater lake, the true beginning of activity cannot be precisely determined and the effusion rate may have actually been lower. If this is not the case, then it is likely that the rise of magma was governed mostly by the hydrostatic pressure, and the gas content was not large enough to allow fragmentation. Aspinall et al. (1972) correctly predicted that during a forthcoming stage, migration of exsolving volatiles from the magma chamber and conduit will lead to build up of gas pressure under the lava plug and its explosive disruption, a stage that eventually took place in 1979. All things considered, it may be expected that high gas content increases buoyancy of the rising magma and, therefore, increases its extrusion rate.

Rapid dome growth, on the other hand, leads to gravitational instability, particularly when the crater floor is inclined towards a breached side and confined by steep cliffs on the remainder of the crater walls. At Mt. Redoubt in 1989–1990, it has been shown that a number of domes growing on a 20° slope became oversteepened and have been almost completely destroyed through gravitational collapse-generating explosive events with a strong lateral component (Miller 1994, p. 208). According to Miller, gravitational collapse occurred when the lava domes reached a volume as low as $3\times10^6 m^3$, well below the volume estimated at Montagne Pelée on 8 May 1902 morning (however on a less inclined slope).

Conclusion

These considerations suggest that the 8 May 1902 eruption of Montagne Pelée could have been triggered by the partial collapse of an already voluminous lava dome whose mass was unstable southward above the deep Rivière Blanche valley. Sudden depressurization of the inner, volatile-rich part of the dome, thus generated a strong lateral explosion, in some way similar to that resulting from a flank failure. Shortly after the 8 May eruption, rapid dome growth would have resumed beneath a plug of viscous residual melt owing to previous exsolution of gas, and gradual increase of internal pressure eventually led to the second climactic outburst of 20 May. The high volatile content, and pressurized gas in the dome interior, could have contributed mechanically to the collapses on 8 and 20 May, as well as to the violence of the collapses (Voight and Elsworth 2000). Then, relatively gas-poor magma fed a less rapidly growing dome and less violent eruptions on 26–28 May, 6 June and 9 July. After a lull, a second batch of volatile-rich magma from depth, or gradual gas accumulation in the upper conduit, caused increasing activity in mid-August that eventually culminated with the destructive nuées ardentes of the 30th. Later batches of gas-poor magma gave way to other pulses of decreasing intensities in November 1902 (great spine), February and August 1903, November 1904 and June 1905, gradually re-equilibrating the magmatic system.

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