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Abstract

Basaltic magma chambers are often characterized by emptying and refilling cycles that influence their evolution in space and time, and the associated eruptive activity. During April 2007, the largest historical eruption of Piton de la Fournaise (Île de La Réunion, France) drained the shallow plumbing system (> 240 × 10^6 m^3) and resulted in collapse of the 1-km-wide summit crater. Following these major events, Piton de la Fournaise entered a seven-year long period of near-continuous deflation interrupted, in June 2014, by a new phase of significant inflation. By integrating multiple datasets (lava discharge rates, deformation, seismicity, gas flux, gas composition, and lava chemistry), we here show that the progressive migration of magma from a deeper (below sea level) storage zone gradually rejuvenated and pressurized the above-sea-level portion of the magmatic system consisting of a vertically-zoned network of relatively small-volume magma pockets. Continuous inflation provoked four small (<5 × 10^6 m^3) eruptions from vents located close to the summit cone and culminated, during August-October 2015, with a chemically zoned eruption that erupted 45 ± 15 × 10^6 m^3 of lava. This two-month-long eruption evolved through (*i*) an initial phase of waning discharge, associated to the withdrawal of differentiated magma from the shallow system, into (ii) a month-long phase of increasing lava and SO_2 fluxes at the effusive vent, coupled with CO_2 enrichment of summit fumaroles, and involving emission of less differentiated lavas, to end with, (iii) three short-lived (~2 day-long) pulses in lava and gas flux, coupled with arrival of cumulative olivine at the surface and deflation.

The activity observed at Piton de la Fournaise in 2014 and 2015 points to a new model of shallow system rejuvenation and discharge, whereby continuous magma supply causes eruptions from increasingly deeper and larger magma storage zones. Downward depressurization continues until unloading of the deepest, least differentiated magma triggers pulses in lava and gas flux, accompanied by rapid contraction of the volcano edifice, that empties the main shallow reservoir

and terminates the cycle. Such an unloading process may characterize the evolution of shallow magmatic systems at other persistently active effusive centers.

1 Introduction

The eruptive evolution of basaltic systems is known to be controlled by several interconnected factors such as supply rate, conduit instability, variation in reservoir geometry, and regional and gravitational stress fields (e.g., Walker, 1993, Wadge and Burt, 2011). The temporal evolution of discharge at a basaltic system has classically been explained by tapping of a single, pressurized chamber (Wadge, 1982). In this case, the frequency and volume of eruptions, the rate at which magma is erupted, and the effusive trends reflect century-scale and short-term (decades–to-years) eruptive cycles (Dzurisin et al., 1984; Harris et al., 2000; 2011) which, in turn, have been linked to the development and disruption of the magmatic system occurring at various levels in the crust and with different timescales (Wadge and Burt, 2011). The waxing-waning discharge trends associated with such a model have been observed at Mt. Etna (Wadge, 1982; Harris et al., 1997; Bencke and Neri, 2003), Nyamulagira (Wadge and Burt, 2011), Kīlauea (Swanson et al., 2014), Mauna Loa (Lipman, 1980), Stromboli (Marsella et al., 2012, Valade at al., 2016), Villarrica and Llaima (Dzierma and Wehrmann, 2010), and have also characterized recent eruptions at Piton de la Fournaise (e.g., Ludden 1977; Peltier et al., 2008). Recently, the role of unloading of deeper magma, through eruption of dense, degassed magma residing in the shallow system, has been evoked to explain explosive "paroxysms" at effusing basaltic systems (Calvari et al., 2011a,b; Valade et al., 2016). This mechanism implies a downward depressurization of the plumbing system that complicate the application of the classical models of output from a magma reservoir (Wadge and Burt, 2011).

We here demonstrate the need to evolve the standard model for emptying a basaltic magma reservoir during a series of effusive eruptions and to define a new model for eruption cycles at a persistently active effusive system. To do this we apply a pan-disciplinary (spanning chemical, textural, geophysical and remote sensing) data set to track the evolution of the plumbing system of Piton de la Fournaise (Île de La Réunion, France) during its eruptive activity in 2014-15. Five eruptive events characterized these two years, and culminated in the voluminous August-October 2015 eruption (Peltier et al., 2016). Following October 2015 the volcano inflated again in a more discontinuously way, and erupted again in May and September of 2016. The data presented here provide a new view on the steps of pressurization, rejuvenation and drainage of a vertically stratified basaltic plumbing system during a series of effusive eruptions.

Figure 1

2 Eruption cycles and recent activity of Piton de la Fournaise

At Piton de la Fournaise (2632 m above sea level) we characterize an eruptive cycle as beginning with a period of shallow intrusions and low-volume summit-proximal activity (vent opening inside the summit crater or at less than 5 km), during which the (re)distribution of the stress field inside and around the edifice favors reorganization and rejuvenation of deeper storage zones (Peltier et al., 2010). This "*replenishment*" stage is followed by a period of high output rate, this being a "*discharge*" phase that culminates in a major effusive eruption that represents final emptying of the shallow system (Michon et al., 2007; Peltier et al., 2009; Swanson et al., 2014) and re-setting of the cycle (Di Muro et al., 2014). Large-volume eruptions thus often mark the end of eruptive cycles that, at Piton de la Fournaise, have been recognized as occurring over time-scales of 2-40 years (Peltier et al., 2008). Early research indicated that periods of high output rate emitted olivine basalts and oceanites (olivine-rich basalts with olivine > 20 vol%), with periods of low output rate emitting more evolved lavas (Ludden, 1977; Lénat and Bachèlery, 1990). However, Roult et al., (2012) failed in identifying a long term cyclic behavior and showed that, while evolved basalts fed short-lived and small-volume summit to summit-proximal eruptions, eruptions with higher output rates and volumes spanned a range of bulk rock compositions from evolved aphyric basalts (MgO ≈ 6wt%) to oceanites (MgO up to 8.7wt% when filtered for the effect of olivine accumulation). Such an eruptive pattern may reflect the interaction between different portions of a vertically-zoned plumbing system where pulses of deep-sourced magma (expected to have >12.5wt% MgO; Albarède et al., 1997) ascending from a reservoir at the crust-mantle interface (i.e., 12-15 km below the summit) are periodically injected into the more evolved and degassed shallow portion of the system (Albarède, 1993; Battaglia et al., 2005; Peltier et al., 2009; Prôno et al., 2009; Massin et al., 2011; Di Muro et al, 2014; Vlastélic and Pietruszka, 2016). The shallowest part of the Piton de la Fournaise plumbing system is located above sea level and consists of a network of relatively small-volume (0.1-0.3 km^3) magma pockets, likely a plexus of dikes and sills, whose location and shape remains a matter of debate (Lénat and Bachèlery 1990; Peltier et al. 2009; Di Muro et al., 2014, 2015; Michon et al., 2016).

A period of intense eruptive activity occurred between 1998 and 2007, when 26 eruptions (Roult et al., 2012; Staudacher et al., 2015) erupted a total bulk volume of ~480 × 10^6 m^3 of lava. These eruptions were subdivided into five short-term cycles of less than 1.5 years in duration by Peltier et al. (2008, 2009). Each cycle began with an initial recharge of the shallow plumbing system and inflation, followed by summit-proximal eruptions (< 5 km from the summit) and slow spreading of the eastern flank (Peltier et al., 2008; Got et al., 2013). Through time, erupted lavas became progressively richer in magnesium. The end of each cycle was represented by a distal (> 5 km from the summit) eruption of oceanite on the eastern flank (Vlastélic et al., 2005; 2007). According to Got et al. (2013), this repeated pattern of activity is related to short-term stress cycles linked to a non-linearity in the stress accumulation in the edifice, and does not necessary reflect changes in the magma supply rate.

During April 2007, Piton de la Fournaise experienced its largest historical eruption (> 200 × 10^6 m^3). The shallow part of the plumbing system drained, erupting olivine-rich cumulates (olivine up to 24% vol; Michon et al. 2007; Di Muro et al., 2014) and resulting in summit collapse to create a caldera with an estimated volume of ~90 × 10^6 m^3 (Staudacher et al., 2009, 2015). Deflation of the whole edifice, very low rates of seismic activity and low temperature H_2O-rich summit fumarolic emissions followed the 2007 eruption, before renewed inflation and magma recharge heralded the beginning of a new eruptive cycle (Di Muro et al., 2012, 2015; Peltier et al., 2009, 2016).

Following 2007 caldera collapse event, the redistribution of the stress field favored arrest of dykes at shallow-depths (1-2 km below the summit) and allowed magma to gather in shallow storage zone (Peltier et al., 2010), as has been evoked to describe the shallow system at Kīlauea (e.g. Fiske and Kinoshita, 1969). These shallow magma pockets subsequently erupted eight times between 2007 and 2010 (Staudacher et al., 2015), feeding small-volume (<3 × 10^6 m^3) eruptions that produced relatively evolved magmas (MgO: 7.1 ± 0.6 wt%, Di Muro et al., 2015; Vlastélic and Pietruszka, 2016) inside, or close to (< 1 km), the summit (Peltier et al., 2010). During this period, the main trend of deflation, consequence of the April 2007 collapse, was only interrupted by pre-eruptive inflation-deflation patterns close in time to each eruptive event (Peltier et al, 2010; Staudacher et al., 2015).

After 41 months of quiescence and continuous deflation, a new phase of activity began in June 2014. The June 2014 eruption was preceded by only 11 days of weak inflation (Fig. 1c; Peltier et al., 2016) and increase of CO_2 soil-degassing on the volcano flanks (Liuzzo et al., 2015). After this short-lived event and until August 2015, deep seismicity increased, inflation accelerated and the composition of summit fumaroles become increasingly CO_2-rich, notably from mid-April 2015 (Lengliné et al.; 2016; Peltier et al, 2016). The activity that followed involved a sequence of four eruptions in 2015, of which the last was by far the longest-lasting and most voluminous (Table 1). It is on this data-rich 2014-2015 cycle (Fig. 1) that we focus.

Table 1

3 Datasets and results

3.1 Time Averaged Lava Discharge Rate

During 2014 and 2015, the MIROVA hot spot detection system (Coppola et al., 2016) provided systematic MODIS-derived spectral radiance data for each eruption. Following the conversion routine calibrated for Piton de la Fournaise by Coppola et al (2009; 2010; 2013), these data were converted to Time Averaged Lava Discharge Rate (*TADR*) and erupted volume (bulk), for each of the five events that comprise the 2014-2015 cycle. An uncertainty of ± 35% in the satellite-derived values reflects distinct eruptive conditions that may characterize the effusive activity of Piton de la Fournaise, such as different emplacement styles (i.e., channel- versus tube-fed) or underlying topography (steep versus shallow slopes). Thus, during the 2014-2015 eruptions upper, median and lower bounds were set on MIROVA-derived TADR to take into account this uncertainty (Figure 2). The comparison between satellite-based estimations with lava volumes derived from photogrammetry and InSAR analysis (Peltier et al., 2016) is shown in Table 1. In the case of the February 2015 eruption the MODIS-derived volumes were likely underestimated, because the satellite overpasses missed the initial phase of the eruption due to the presence of clouds. On the contrary for the other four eruptions the comparison reveals that the thermal approach provides correct estimates, within the uncertainty considered. It is worth noting that during small-volume ($< 3\times10^6$ m^3), short-lived (< 2 days) eruptions the MODIS-derived values were slightly underestimated, while during the longer and most voluminous eruptions, the MODIS-derived values were overestimated. This difference may be due to the low sampling time of MODIS (~4 overpasses per days) that is not sufficient to track with precision short-lived effusive events (Coppola et al., 2016). However, it may also reflect the different emplacement styles and insulation conditions that characterize short- and long-lived eruptions. In any case, both conditions are efficiently embedded within upper and lower bounds of MIROVA-derived TADR that are set during each eruption.

Eruption duration, erupted volume (*Vol*), peak *TADR* and mean magma output rate (*MOR*) are summarized in Table 1 . The first four events had *TADR* and cumulative volume trends (Fig. 2a-d) that displayed the classic rapid-waxing and slow-waning forms that characterize eruption from a pressurized source, as defined by Wadge (1981). For these four short-lived events, the cumulative volume trends can be described using an exponential asymptotic growth trend (R^2>0.9), with the form (Fig. 2),

$$V(t) = V_e[1-exp(-t/\tau)]$$

in which V_e and τ are the final lava volume (0.4–7 million m^3) and the time-decay constant (0.8–4.2 d), respectively (Table 1). Conversely, the fifth (final and longest) eruption in the cycle had (after a short and very intense initial peak reaching 60 m^3/s) an initial phase of slightly decreasing output (Fig. 2e) followed by an increase of *TADR* from less than 10 m^3/s between 25 August and 13 October to more than 20 m^3/s between 14 and 17 October, when the eruption suddenly stopped. The two *TADR* spikes at the end of the eruption (Fig. 2e) record two short-lived events with peaks at 32 and 20 m^3/s, respectively, and correspond to two reactivations of the eruption from the same vent on 23 and 30 October, respectively. An abrupt cessation in lava effusion followed the pulse that ended the main phase of effusion and separated the two reactivation events. Each reactivation event was separated by exactly seven days from the preceding activity and lasted for two days. The August-October 2015 event can thus be divided into three phases (Fig. 2e – 4a) defined by the following volumetric characteristics:

(i) an initial slightly decreasing phase (24 August – 10 September; volume = 10.8 ± 3.7 × 10^6 m^3), following a short lived phase of intense effusion during the first day

(ii) a month-long phase of increasing TADR (11 September–13 October; volume = 22.2 ± 7.7 × 10^6 m^3), and

(iii) three short-lived (~2 day-long) pulses after 14 October (total volume = 12.2 ± 4.2 × 10^6 m^3),

for a total erupted volume of 45.2 ± 15.6 × 10^6 m^3.

Figure 2

3.2 Deformation

The inter-eruptive deformation pattern observed between 9 June 2014 (11 days before the first eruption of the 2014-2015 cycle) and 24 August 2015 involved nearly continuous edifice inflation (Peltier et al., 2016), which accelerated in mid-April 2015 when deep seismicity and CO_2 enrichment of summit fumaroles was first detected (Fig. 1c).

Syn-eruptive deformation revealed that the decrease in TADR observed during the first four eruptive events was coupled with a parallel deflation of the summit cone (Fig. 3). The occurrence of such a trend is especially evident for those events that lasted more than one week, such as the February (Fig. 3b) and May (Fig. 3c) 2015 eruptions. For these eruptions, the balance between the volume of the pre-eruptive sources, deduced from inversion of the deformation data (see Fig. 4 of Peltier et al., 2016) and corrected for compressibility, is – to an order of magnitude –equal to the erupted volume (Table 1). Conversely, for the 68-day-long August-October 2015 eruption, the estimated pre-eruptive volume source (Peltier et al., 2016) is about ten times greater than the erupted volume (Table 1), also taking into account a correction of ~40% for vesicularity (Di Muro et al., (2014). This suggests that most of the erupted volume involved a significant contribution from deeper (below sea level) regions (Peltier et al., 2016).

The deformation pattern observed during the final and largest event (Fig. 4b) was different from that of all previous events. It involved a first phase of moderate summit deflation (24 August – 5 September), followed by summit inflation between 6 and 25 September, with deflation then persisting until the end of the first eruptive phase (Fig. 4b). The two last pulses of activity (22-24 October and 29-31 October) were each preceded by renewed summit inflation and accompanied by summit deflation. Deformation and TADR were well correlated until 25 September when they became anti-correlated (Fig. 4b). This implies that, during the first half of the eruption, the shallow magmatic system underwent a draining-refilling sequence, whereas the second and terminal stages of the eruption were characterized by fast emptying of the plumbing system.

Figure 3

3.3 Gas fluxes at the vents

The time evolution of the SO_2 emission, plume altitude and direction were captured by the scanning DOAS (Differential Optical Absorption Spectroscopy) network installed by NOVAC (Galle et al., 2010) during four of the five eruptions treated in this paper (Fig. 3-4). Galle et al. (2010) estimates a typical uncertainty of 26% for good measurement conditions and 54% for fair measurement conditions for the NOVAC-type scanning-DOAS instruments used in this study. Bad weather prevented acquisition of a reliable SO_2 time series during the February 2015 eruption. During the June 2014, May 2015, and July-August 2015 eruptions, SO_2 emission rates decayed in a manner consistent with trends observed in the TADR time series (Fig. 3). Total SO_2 emissions for these three events were at least 85, 4800, and 218 t, respectively (Table 1).

On 24 August 2015, the network missed a portion of the initial, short-lived, phase of high TADR that characterized the August-October 2015 event, as this occurred during the night. However, from the temporal trend in SO_2 emission that followed (Fig. 4c), it is possible to identify the following phases:

(i) a sharp and short-lived increase at the eruption beginning, followed by a lower and generally steady emission rate between 24 August and 8 September and then a marked decrease between 8 and 12 September. SO_2 emissions remained at very low level up to 14 September;

(ii) a progressive increase between 14 September and 13 October. Plume geometry and changing weather conditions resulted in fluctuating SO_2 emissions before 3 October;

(iii) three discrete pulses between 14 October and 1 November;

The daily SO_2 flux was highest at the very beginning of the eruption (on 24-25 August) and during the pulsating period 14 – 30 October. During most of the eruption, the SO_2 flux was less than 2 kt/d, punctuated by peaks at 5.5-6.7 kt/d on 25 August, 25 September and 17 October. Daily SO_2 fluxes increased from <0.6 kt/d during the first phase, to 0.8 - 1.4 kt/d during the second and third phases, with the most intense phase of SO_2 outgassing beginning on 14 October, and overlapping with the syn-eruptive deflation recorded by the deformation network (Fig. 4c). The temporal variation in the emission rate of SO2 during this event mimics in general that of the TADR (Fig. 4). However, some discrepancies can be seen during 11-17 September and 1-6 October, when an apparent reduction in SO2 emission rates is observed though the TADR remained at high levels. The first discrepancy (11-17 September) corresponds to a period of hazy weather with relatively little rain and a low altitude gas plume, partly confined inside the caldera. The second discrepancy (1-6 October) corresponds to a period of intense rain, which likely produced wet deposition of SO_2 and poor measurements conditions. Consequently, in both periods the SO_2 emission rate was most likely underestimated, explaining the discrepancy with the TADR. Overall, both the SO_2 flux and TADR time-series indicate that gas and lava discharge increased during the last third of the eruption, i.e., between 14 and 30 October. The increase in TADR between 15 and 17 October was also associated with an increase in plume height, and the final two TADR spikes were associated with daily SO_2 fluxes of 1500 and 940 t/d, respectively.

An estimation of the pre-eruptive magma sulfur content was obtained by scaling the total SO_2 output to the mass of erupted lava (Table 1) while assuming a bulk vesicularity of 40 % and a melt density of 2800 kg/m^3, as documented by Di Muro et al., (2014) and validated by Hibert et al., (2015). Results for both the May and August-October 2015 eruptions indicate similar low pre-eruptive volatile contents, of ~600 ppm. This value is about 3/5 of that recorded by most melt inclusions for magmas stored near-sea-level at Piton de la Fournaise (see Di Muro et al., 2016 for review). These values suggest that erupted magmas experienced significant pre-eruptive outgassing at a level shallower than sea level before being erupted.

Figure 4

3.4 Summit fumarole compositions

A permanent MultiGaS station installed on the southern rim of the Dolomieu caldera (see Fig. 1a for location) allowed us to track the daily evolution of gas emissions at the summit of Piton de la Fournaise (Di Muro et al., 2012; Peltier et al., 2016). Analysis of long-term trends reveals that, during quiescent phases, emissions from low temperature fumaroles at the summit are dominated by vapor water, with very small CO_2 and H_2S amounts (Di Muro et al., 2012). However, the reactivation in 2014-2015 was detected by a change in the composition of summit emissions, with increasing contributions of H_2S and CO_2 and low amounts of SO_2 (average H_2S/SO_2 molar ratio = 16). In particular, CO_2/H_2S and CO_2/H_2O ratios increased during deep seismic events (down to 9.5 km below the volcano summit) below the central cone in mid-April 2015 (Peltier et al., 2016). Here we use the CO_2/H_2S ratio as a reference to describe the time evolution of CO_2 enrichment in summit emissions during each eruption (Figs. 3-4). This ratio is selected because of the generally low and, relatively stable, H_2S concentrations and because this ratio is less affected (in respect to CO_2/H_2O) by condensation effects. The molar ratio is calculated after subtraction of the modeled atmospheric background. CO_2/H_2S molar ratios increased before the eruptions of February, May and July 2015 (Figs. 3b,c,d). The peak in CO_2/H_2S was measured 2-10 days before (February and May 2015) or 1-3 days after (June 2014 and July 2015) each eruption onset and decreased during the following days. In contrast, during the August-October 2015 eruption, CO_2/H_2S attained a first maximum at the beginning of the eruption (between 24 and 28 August). It then decreased before increasing again between 22 September and 1 October (Fig. 4c). A third phase of CO_2 enrichment was detected towards the end of the eruption during 17-19 October, and again after the eruption end. The strongest CO_2 enrichment was broadly synchronous with the syn-eruptive resumption of inflation and the increase in SO_2 emission (Fig. 4b-c).

3.5 Geochemical and Petrological Evolution

Lavas erupted between June 2014 and May 2015 showed a decreasing trend in MgO (6.6 to 6.1 wt %), Ni (92 to 65 ppm), Cr (87 to 58 ppm), and CaO/Al_2O_3 (from 0.78 to 0.73) consistent with sampling a differentiating magma reservoir with time (Fig. 5). Elevated and increasing Fe_2O_3 contents (from 12.6 to 12.9 wt %, compared with <12.4 wt % in 2010) indicate that Fe behaved as an incompatible element. This implies that olivine was no longer at the liquidus so that, probably, magma temperature had decreased below 1150 °C (Villemant et al. 2009; Di Muro et al., 2016). The lavas erupted on 17 and 18 May 2015 were aphyric basalts with rare tabular plagioclase microphenocrysts (up to 200 µm in length, An_{70} to An_{60}), and were amongst the most differentiated of those sampled during Piton de la Fournaise historical record, resembling products emitted in March 1998 after 5.5 years of quiescence (Vlastelic et al. 2005; Boivin and Bachèlery, 2009). However, a change in behavior occurred during the May 2015 eruption when, between 18 and 24 May, the temporal trends in MgO, Cr, Ni and CaO/Al_2O_3 reversed (Fig. 5a-b). The new trend was initially subtle but became more evident during the subsequent eruptions of July-August 2015 and, especially, during the August-October 2015 event. MgO and CaO/Al_2O_3 increased continuously from 6.6 wt% and 0.80 at the beginning of this large final eruption to 11.03 wt% and 0.89 at its end (Fig. 5a-b). The CaO/Al_2O_3 ratio of 0.894 for the last lava erupted was amongst the highest ratios measured in historical lavas of Piton de la Fournaise (Albarède et al., 1997) and indicates unusually low pyroxene fractionation or pyroxene assimilation. The compositional trend reversal that occurred in May 2015 can be ascribed to the input of less differentiated magmas. The concomitant La/Sm ratio decrease (Fig. 5c) can also be explained by the same process, by the delivery of high-degree of melting from the mantle, or both.

Mixing between (i) differentiated magma (represented by lava erupted in May 2015), (ii) new, less differentiated magma (represented by the October 2015 lavas - corrected for olivine addition), and (iii) cumulitic olivine, has been modeled in MgO-Fe_2O_3 concentration space (Fig. 5d). The model points to a temporal decrease in the differentiated component after May 2015, with the contribution of cumulitic olivine progressively increasing during October 2015 to reach around 12 wt% by the end of the August-October 2015 eruption (Fig. 5e). We stress, however, that the new mafic input (MgO 7wt%) remains relatively evolved with respect to the mafic melts (MgO 7.4-8.7 wt%) involved in the 2007 and 2008 eruptions (Villemant et al., 2009; Di Muro et al., 2014,2016).

Petrological investigations carried out on quenched samples collected during the July-August and August-October 2015 eruptions highlight a change in phenocryst content. In the July-August and August to early-September 2015 lavas, phenocrysts (up to 1 mm in size) consisted of faceted crystals of plagioclase (An_{85} to An_{67}) and clinopyroxenes, with rare and small olivines. While plagioclase content then decreased during the second half of September, lavas emitted in October were richer in mm-sized olivines (Fo_{83}) containing Cr-spinel as inclusions. Comparison of geochemical and TADR data (Fig. 1) indicates that the compositional trend can be linked to a transient increase in lava discharge (from 4 to 7 $m^3 s^{-1}$) that occurred on 23 May 2015. In addition, while cumulitic olivine began to appear in lavas erupted between 9 and 16 October, lava discharge increased from less than 10 m^3 s^{-1} on 12 October to 22 m^3 s^{-1} on 15 October (Fig. 4). Such relations are consistent with coupled geochemical and lava discharge trends observed during 2002-2006 olivine-rich eruptions (Vlastélic et al. 2007).

Figure 5

4 Discussion

The 2014-2015 datasets reveal a progressive rejuvenation of the shallow plumbing system of Piton de la Fournaise during which new, less differentiated magma (MgO ≈ 7wt%) began to mix with partly outgassed and more differentiated magma (MgO ≈ 6wt%) resident in the shallow system. We term this the "*rejuvenation* (*loading*)" phase of the shallow system. Increases in summit CO_2 emissions suggest that a simultaneous pressure buildup at shallow levels (above or close to sea level) was driven by a deeper source. Gradual pressurization of the shallow system during loading thus triggered the first four eruptions, from June 2014 to July-August 2015 that drained separate, small-volume (Ve = 0.4–7 × 10^6 m^3) pockets of degassed magma or, alternatively, different parts (compartments) of a single cooling reservoir, which was initially filled by differentiated magma (T < 1150 °C). All four of these eruptions were characterized by lava discharge rates that decayed rapidly with time (τ = 0.7-4.2 days) and which were coupled with syn-eruptive deflation of the summit (Fig. 2-3). This pattern is consistent with rapid withdrawal of magma from a pressurized source (Wadge et al., 1981), without any new deep input during the eruption, with a progress emptying and closure of the dike. In this case the volume of erupted lava (Ve) and time-decay constant (τ) are proportional to the capacity (C) of the pressurized source ($Ve=CP_0$; where P_0 is the initial overpressure) and to the hydraulic resistance of the eruptive dikes ($R=1/\tau C$) (Aki and

Ferrazzini, 2001). According to Peltier et al., (2016), the pressure sources inferred from inter-eruptive deformation data were located at depths ranging from 1.3 to 3.7 km below the summit. Our datasets reveal that the depth of these pressure sources strongly affected the effusive development of the associated eruption. In particular we find that the time-decay constant ($\tau=RC$) of these small-volume, pressurized eruptions is linearly correlated with the depth of the pressure source (Table 1), suggesting that pressure buildup at shallower levels in the magmatic system involved magma storage zones with lower capacity and/or with reduced channel resistance. Measured SO_2 fluxes mirror the effusive trends (Fig. 3-4) and total SO_2 outputs scale proportionally to the emitted lava volumes (Table 1), suggesting that sulfur was essentially released by ascending and decompressing magma without significant pre-eruptive accumulation at depth. On the other hand, our data reveal that magmas erupted after the 2010-2014 quiescence pause were largely outgassed before eruption. This is consistent with the dominantly evolved compositions of most of the erupted products.

4.1 Discharge (unloading) of the shallow magmatic system

The initial phase of the August-October 2015 eruption was characterized by waning lava discharge, general decrease in gas emissions and deflation (Fig. 4), typical of pressurized eruptions. Such a trend persisted until 10-13 September and is interpreted to be associated with the withdrawal of magma stored within a shallow, stratified reservoir. We can model this initial effusive trend (blue dashed line in Fig. 4a) using the pressurized eruption model of Equation 1, and find that the reservoir involved in the August-October 2015 eruption was initially drained with a decay constant of 34 days, which is 10 to 100 times longer than those of the previous four eruptions (Table 1). This likely reflects a larger capacity of this reservoir to store magma compared with previous ones. However, a magnesium-rich magmatic source became evident in exact correspondence with a new period of inflation, increase in lava and SO_2 emissions and strong CO_2 enrichment in summit fumaroles (Fig. 4) that defined the beginning of the second phase of the eruption, a phase that all other eruptions in the cycle lacked (c.f. Fig. 3). The relative contribution of less differentiated magma increased rapidly in the days following this transition, as witnessed by the reversal in compositional trend of the erupted lavas (Fig. 5). New magmatic injection at this time is consistent with enrichment in deep fluid signatures (CO_2) of the hydrothermal intra-caldera fluids emitted by the summit fumaroles (Fig. 4d). In this scenario, the peak in SO_2 and CO_2 emissions, recorded on late September (Fig. 4c), likely represents the buffered response of the shallow system to this deep pulse. This evolution suggests that deep magma was injected into the shallow reservoir at this point.

However, after 25 September 2015, lava discharge and the summit deformation became anti-correlated, with increasing lava flux coupled with accelerating contraction of the summit (Fig. 4a-b). The gradual intensification of the eruption was coupled with involvement of a more mafic melt and an increase in the presence of olivine phenocrysts in the erupted lavas, as well as an increase in SO_2 emissions (Fig. 4). This process accelerated on 13 October and appears to have been the first of three consecutive pulses that characterized the third, terminating phase of this "*cycle-ending*" eruption. High lava and gas discharge rates characterized these terminal pulses, which lasted ~2 days each. The pulses were associated with short lived edifice contraction, followed by abrupt cessation of effusive activity (Fig. 4). This final phase produced a volume of 12.2 ± 4.2 million m^3 of lava and emitted the most magnesian and cumulative olivine-rich lavas of the entire cycle. Notably, the three pulses were separated by two hiatuses lasting exactly six days each, during which CO_2 enrichment of the summit fumarole emission was accompanied by reappearance of summit inflation (Fig. 4). The change in the TADR-deformation relationship during the final phases of this terminating eruption, and the rapid edifice contraction, support a model whereby the eruption rate began to exceed the magma supply rate, thus causing partial emptying of the shallow reservoir, contraction of the volcano edifice and culminating in high lava discharge during the arrival of cumulate-olivine in the erupted lava. We thus suggest that the "*unloading*" of the deepest mass, initially injected into the base of the shallow plumbing system at the beginning of the cycle, contributed to the short, high discharge rate pulses that characterized the final days of the 2014-2015 cycle.

Figure 6

4.2 Shallow system rejuvenation and discharge trends at Piton de la Fournaise

The sequence of events and trends observed in the datasets collected during 2014 and 2015 allows us to propose a schematic model for an unloading plumbing system at a persistently active basaltic system (Fig. 6). At Piton de la Fournaise, the system is composed of a main magma reservoir (located ~2.5 km below the summit), above which an interconnected network of small, cooling magma pockets is proposed to reside. In this model, the whole system is vertically structured, chemically stratified, and filled by evolved and partly outgassed magma. While pulses of deeper and less-evolved magma supply the system at its base, an olivine-rich crystal-melt mush forms at the cooling margins. Plagioclase and pyroxene become important phases in these shallow outgassed "*pockets*" of relatively evolved and cooled magma. During a cycle of magma rejuvenation and discharge the ascent and arrival of deep magma into the plexus causes continuous inflation accompanied by CO_2 enrichment in summit fumaroles. At the beginning of the cycle, pressurization is sufficient to trigger eruption of the shallow magma pockets filled by the most evolved and degassed magma. This results in short-lived, small-volume eruptions characterized by fast waxing-waning discharge trends. As deeper magma continues to arrive, inflation steadily continues and increasingly large volumes of magma are pressurized and erupted. This promotes a downward depressurization that proceeds until the drain of the deeper stratified and volatile-rich reservoir begins. A key point is that, at Piton de la Fournaise, water and sulphur exsolution accelerate when magma is at pressures lower than 1 kbar (Di Muro et al., 2015a; 2016), thus providing the trigger for a buoyancy increase and greater magma ascent rate. Together with the eruptions of smaller magma pockets, the withdrawal of magma from the larger reservoir "*unloads*" the deepest mass, which has been gradually injected into the base of the system during the cycle. This process triggers a sharp intensification of the effusive phase, coupled with high discharge-rate eruption of the olivine-rich mush/melt and the rapid contraction of the volcano edifice (Di Muro et al., 2014), which terminate the 2014-2015 cycle.

The unloading process described above displays several similarities with the mechanisms supposed to drive explosive (basaltic) paroxysms (e.g. downward depressurization, Calvari et al., 2011a-b, Valade et al., 2016), although differs in the time scale (days rather than minutes to hours), intensity (~10^1 m^3/s rather than 10^2-10^3 m^3/s; cf. Calvari et al., 2011a-b) and final result (pulses in lava effusions rather than explosive eruptive columns). Thus, we introduce the term "*effusive (basaltic) paroxysm*" to describe an accelerating effusing phase, accompanied by sharp contraction of the volcano edifice, and related to the unloading of buoyancy-driven, deep mass which ascends rapidly to feed a short, highly energetic, high mass flux event.

5 Conclusions

By coupling multiple datasets recorded at Piton de la Fournaise between 2014 and 2015 we were able to track and parameterize a complete cycle of shallow-system rejuvenation and discharge. During the *rejuvenation* stage of June 2014 - July 2015 we observed:

- Progressive arrival of deep magma marked by deep earthquakes, continuous inflation and CO_2 enrichment in summit fumarole emissions (Lengliné et al., 2016; Peltier et al., 2016);
- Downward depressurization during sporadic drainage of the shallow magmatic system associated with rupturing of increasingly deep and voluminous magma pockets filled with less differentiated magma.

Conversely, during the *discharge* phase we observe the following features:

- Initial drainage of a larger (but still shallow) magma reservoir; followed by

- Increasing lava and gas flux coupled with inflation of the summit cone, with erupted lavas becoming increasingly less evolved; to result in an
- Impulsive pattern characterized by a sequence of three effusive pulses (TADR ≈ 30 m^3/s and SO_2 fluxes ~ 5000 t/d), accompanied by rapid deflation of the summit (hereby defined "*effusive paroxysms*").

Unloading of basaltic systems can thus explain not only explosive events that punctuate eruptions at effusive basaltic centers such as Stromboli and Etna (Calvari et al., 2011a-b, Valade et al., 2016), but may be at the origin of many other "*effusive paroxysms*" reported for example at Villarrica (as during the 1972 eruption), Llaima (Bouvet de Maisonneuve, et al., 2013) and Kliuchevskoy (Van Manen et al., 2012). The real-time quantification of Time Averaged Lava Discharge Rate (TADR), gas flux, deformation and petrology during further events can thus shed light on the dynamics characterizing the rejuvenation-discharge phases at systems prone to "*effusive paroxysms*", and can allow a degree of forewarning of such events.

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Tables

Table 1: Main parameters for the 2014-2015 eruption of Piton de la Fournaise (all times UTC).

(1) Values derived from MODIS data: *Vol*: erupted volume (bulk) estimated; max*TADR*: Maximum Time Averaged Lava Discharge Rate; *MOR*: Mean Output Rate.

(2) Values derived from model: exponential parameters and correlation coefficient obtained by fitting MODIS data with equation $Vout = Ve[1\text{-}exp(-t/\tau)]$; *Ve* is the final lava volume and τ is the decay time constant. See the text for more details. * Best-fit parameters relative to the August-October 2015 eruption were retrieved for eruptive days 2 to 16.

(3) Erupted bulk lava volumes (Vol_{lava}) deduced from photogrammetry and InSAR analysis. Source parameters (volume and depth) inferred from pre-eruptive deformation data (from Peltier et al., 2016);

SO_2: Total mass of SO_2 measured by the DOAS-NOVAC network.

Figure Captions

Figure 1 - (a) Shaded relief map of Piton de la Fournaise and monitoring network used in this work. Red, green and blue transect represent the GNSS baselines shown in (c). (b) Time Averaged lava Discharge Rate (TADR) derived from MODIS data (red line) during the five eruptions between 2014 and 2015. The mean output rate (MOR) of each eruption is represented by the black line. (c) Deformation of the volcano edifice as recorded by GNSS baseline variations (syn-eruptive deformation has been removed). (d) SO_2 fluxes (daily average) measured by the permanent DOAS-NOVAC network. The gray bars outline the periods of effusive activity related to the June 20-21, 2014, February 4-15, May 17-30, July 31 – August 2, and August 24 – October 31, 2015 eruptions.

Figure 2 - Time-series of MODIS-derived TADR (black circles) and cumulative volumes (red circle) for the 2014–2015 eruptions of Piton de la Fournaise (uncertainties are represented by thin lines). Note the waxing and waning trends that characterize the first four eruptions (a-d), typical of pressurized magmatic systems. The best-fit exponential curve for cumulative volumes is calculated using equation 1. The exponential coefficients for each eruption are reported in Table 1. The August-October 2015 eruption (e) display a composite trend, reflecting an eruptive dynamic more complex than the one for the previous eruptions (see the text for details).

Figure 3 – Multi-parametric dataset recorded during the first four eruptions (gray fields) of the 2014-2015 cycle. The exponential decrease in discharge of lava (red) is accompanied by a coeval decrease of SO_2 flux (green) and by deflation of the summit cone (SNEG-DSRG baseline; black), consistent with the fast drainage of magma. CO_2/H_2S molar ratios (blue) increased after the June 2014 eruption, and before the eruption of February, May and July 2015 and decreased to background values afterwards. No evident sign of magmatic refilling is observed during the course of these four eruptions.

Figure 4 – Multi-parametric dataset covering the August-October 2015 eruption. (a) Time Averaged Lava Discharge Rate (red squares) and temporal evolution of MgO content in the erupted lavas (yellow diamond). The blue dashed line outlines the effusive trend modeled during the initial drainage of the shallow reservoir. (b) Syn-eruptive deformation of the summit as shown by distance change on the SNEG-DSRG baseline (black circle). Note the correlation and anti-correlation with TADR (dashed line) recorded before and after 25 September, respectively. (c) SO_2 flux in the plume emitted at the vent (green triangles) and recorded by the NOVAC network. (d) CO_2/H_2S molar ratio in the summit fumaroles (blue circles) recorded by the MultiGaS station. Dark gray fields mark the three main eruptive phases discussed in the text.

Figure 5 - Whole rock (a-b) major and (c) trace element composition plotted versus time. Gray fields outline the five eruptive periods. Dashed lines indicate (1) the compositional trend reversal (between 19 and 23 of May 2015), which is ascribed to the delivery of new, less differentiated magma, and (2) the onset of cumulative olivine occurrence during the long-lived August-October eruption (between 9 and 16 October, 2015).(d) Three component mixing model. Mixing proportions are calculated in the MgO- Fe_2O_3 concentration space. Mixing components are (1) May 2015 magma (MgO= 6.0 wt.%, Fe_2O_3=12.87wt%), (2) October 2015 magma corrected for olivine addition (MgO= 7.0 wt.%, Fe_2O_3=12.05 wt%), and olivine (MgO= 43.3 wt.%, Fe_2O_3=17.2 wt%). (e) The time evolution of the mixing model point toward temporal increase in the less differentiated component after May 2015, with the contribution of cumulative olivine appearing only during the second half of the August-October 2015 eruption.

Figure 6 –Sketch model of the plumbing system of Piton de la Fournaise. The progressive arrival of deep MgO-rich magma pulses causes the gradual pressurization the shallow plumbing system. Progressive tapping of increasingly deep and voluminous magma pockets filled with less

differentiated magma causes downward depressurization that continues until the largest stratified reservoir starts to drain. ”Unloading” of the deepest mass that was initially injected into the base of the system contributes a final, short, high effusion rate phase in the final days of the cycle that causes the rapid contraction of the volcanic edifice and favors the disaggregation of olivine cumulate from the crystal/melt mush.