Paper for submission to the Geological Society of London Special Publication
"The Role of Volatiles in the Genesis, Evolution and Eruption of Arc Magmas"

Prolonged Sulfur Dioxide Degassing at the Soufrière Hills Volcano, Montserrat, and implications for deep magma permeability

Thomas Christopher [1]*, Marie Edmonds [2], Benoit Taisne [3], Henry Odbert [4], Antonio Costa [5], Victoria Hards [6], Geoff Wadge [7]

1. Montserrat Volcano Observatory, Salem, Montserrat, West Indies.
2. Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge, Cambridgeshire UK,CB2 3EQ
3. Earth Observatory of Singapore, Nanyang Technological University, 50 Nanyang Avenue, N2-01B-25 Singapore 639798
4. School of Earth Sciences, University of Bristol, Wills Memorial Building, Queen's Road, Bristol BS8 1RJ, UK
5. Istituto Nazionale di Geofisica e Vulcanologia - Sezione di Bologna, Via Donato Creti, 12, 40128 Bologna, Italy Tel: (+39)0816108446
6. British Geological Survey Environmental Science Centre Nicker Hill Keyworth Nottingham NG12 5GG
7. Environmental Systems Science Centre, University of Reading, Reading, UK

*corresponding author; Thomas@mvo.ms

Words = 6743   References = 118   Tables = 1   Figures = 9

Abbreviated Title: Prolonged SO_2 degassing at Souf Hills

Abstract

The installation of a network of UV spectrometers on the western flank of the Soufrière Hills volcano has produced a robust dataset of sulfur dioxide fluxes over a thirteen year period (2000-2013). The emission of SO_2 has been quasi-continuous over the course of the eruption which is in contrast to the highly discontinuous eruption of lava. Analysis of the flux time series indicates that a degree of periodicity is present in the SO_2 signal, ranging from hours to years. Previous studies show that pulses in the SO_2 flux of ≤ 50 days can be correlated with other volcanic activity such as seismic activity and extrusion. We identify two longer period signals in the SO_2 data, one at ~ 5 months and the other at ~ 2 years, which are independent of lava extrusion and ground deformation. We investigate possible causes of these periodic degassing signals, e.g. hydrological, atmospheric, and magmatic controls. We hypothesize that the trends in the degassing time series are sourced from deeper levels in the volcanic plumbing system, related to deformation of the lower reservoir which brings about localized pressure changes. We also discuss the mechanisms by which the sulfur-rich gases might reach the surface.

INTRODUCTION

Understanding volcanic sulfur dioxide (SO_2) degassing processes is an important tool for the monitoring of volcanoes e.g. (Casadevall et al., 1983; Bluth et al., 1994; Fischer et al., 1994; Young et al., 1998a; Aiuppa et al., 2009; Werner et al., 2013). Sulfur emissions from volcanoes have been used to forecast the onset of impending eruptions (e.g. Caltabiano et al., 1994) or to assess the level of activity during an ongoing eruption (e.g. Casadevall et al., 1983; Gerlach and McGee, 1994; Mc Gee and Sutton, 1994; Hirabayashi et al., 1995; Luckett et al., 2002; Zobin et al., 2008; Komorowski et al., 2010). In recent years, long time series of SO_2 emissions have been built owing to recent developments in low-cost automated spectrometer networks which operate in the ultra-violet region of the electromagnetic spectrum, allowing SO_2 fluxes to be measured every few minutes through daylight hours using Differential Optical Absorption Spectroscopy (DOAS; e.g. Edmonds et al., 2003a; Galle et al., 2003; Mc Gonigle et al., 2003). Soufrière Hills Volcano was the first focus of this volcano-monitoring development (Edmonds et al., 2003a; Christopher et al., 2010), and consequently there now exists an unprecedented 18-year long time series of SO_2 emissions, the last 11 years a result of the spectrometer network. Over the course of the eruption, the time series has lent insight into magma supply and eruption processes (Edmonds et al., 2001; Edmonds et al., 2003b; Young et al., 2003; Edmonds et al., 2010; Christopher et al., 2010; Nicholson et al., 2013), and has been used for volcano monitoring and hazard assessment.

The andesite erupted over the course of the 1995-current eruption exhibits a wealth of disequilibrium features on a range of scales, as well as decimeter-sized mafic enclaves (Murphy et al., 1998; Murphy et al., 2000; Humphreys et al., 2009a; Barclay et al., 2010; Plail et al., in press). The andesite is the result of a complex magma genesis, dominated by magma mixing and fractional crystallization during its long residence in an upper-mid crustal magma reservoir (Murphy et al., 1998; Murphy et al., 2000; Zellmer et al., 2003; Humphreys et al., 2009a; 2009b; Humphreys et al., 2012; Christopher et al., in press), in common with other andesite systems (e.g. Fichaut et al., 1989; Sato et al., 1999; Martel et al., 2006; Kent et al., 2010; Ruprecht & Plank , 2013). The resulting hybrid magma contains ~ 45 vol% phenocrysts of plagioclase, orthopyroxene and hornblende (Murphy et al., 1998; 2000), in a rhyolitic melt.

The volatile budget of such an open system is likely to be complex. The low concentrations of sulphur in the plagioclase-hosted melt inclusions (<100 ppm, Edmonds et al., 2001) is not sufficient to account for the mass of sulfur degassed during the eruption (which would require melt concentrations of >1000 ppm sulfur; Christopher et al., 2010). This observation of "excess sulfur" is in common with most other oxidized intermediate-silicic volcanic systems worldwide (e.g. Andres et al., 1991; Gerlach & McGee, 1994; Wallace, 2001; Wallace, 2005; Shinohara et al., 2008a; Wallace and Edmonds, 2011). Much of the sulfur in the system exists in the vapour phase prior to magma ascent and eruption, and the vapour is probably replenished by intruding mafic magma, either through second boiling during crystallization at the interface between the two magmas, or by changes in solubility caused by the contrasting temperatures and/or oxygen fugacity (Christopher et al., 2010; Edmonds et al., 2010; Edmonds et al,. in press).

This kind of mechanism for volatile transfer has also been proposed to explain the sulfur budget of Pinatubo (e.g. Westrich & Gerlach, 1992; Wallace & Gerlach, 1994; Kress, 1997) and Unzen (e.g. Sato et al., 2005; Ohba et al., 2008; Shinohara et al., 2008b). The strong partitioning of sulfur into a hydrous vapor is consistent with thermodynamical and experimental studies which suggest that for oxidized silicic melts, the solubility of sulfur is low (Scaillet & Pichavant, 2003; Clemente et al., 2004; Moretti & Papale, 2004).

The flux of SO_2 gas from the volcano is observed to be variable on a range of timescales. The variability has been attributed to shallow magma permeability during "stick-slip" eruptive behavior (Watson et al., 2000), changes in lava extrusion rate (Young et al., 1998a; Luckett et al., 2002) and over months to years timescales, sealing caused by the precipitation of silica in the conduit and dome between eruptive phases (Edmonds et al., 2003b). Cyclic changes in SO_2 on a timescale of ~50 days have been linked to cyclicity in lava extrusion and seismicity (Luckett et al., 2002; Norton et al., 2002; Loughlin et al., 2010; Nicholson et al., 2013).

There remains, however, some unanswered questions regarding the emission patterns of volcanic gases from Soufrière Hills, and some features of the dataset that make this eruption unique in our view. The first is that over timescales of months to years, the emission of SO_2 appears to be decoupled from the eruption of lava. In general, as much SO_2 degasses when the volcano is not erupting as when it is erupting. Eruptive pauses last 12 to >24 months, and during these relatively long periods SO_2 fluxes are frequently sustained at levels of >500 t/d for weeks to months. This observation requires some deep-seated permeability or advection of the gas phase to be operating, allowing gas to migrate through crystal-rich andesite at depth. Over the dataset as a whole, there are three long period cycles of SO_2 increase and decrease that bear no obvious relation to the eruptive periods (Figure 1).

The second, related puzzle is that, in the 18th year of quasi-continuous degassing, and in the absence of volcanic activity since February 2011, it would be a useful exercise to evaluate what sort of degassing signature might herald the end of the eruption. Are the continued high fluxes of SO_2 at the surface (>300 t/d) indicative of continued supply of mafic magma at depth, or is it possible that the long-lived, large magma reservoir might be able to supply gas in the absence of new magma, for this kind of extended period? These questions have important implications for monitoring and hazard. In this paper, we present the full time series of SO_2 data, from July 1995 to July 2013. We evaluate the possible controls on the long timescale periodicity in the timescale, including gas scrubbing/hydrological control, modulation by a lava dome, and deep magma supply and convection processes. We then discuss the implications of our model for the longevity of the degassing process after the end of the eruption.

ERUPTION OVERVIEW

The Soufrière Hills volcano is an andesitic lava dome complex on the island of Montserrat in the lesser Antilles arc. The current eruption began on the evening of July 18th 1995 with ash venting followed by phreatic explosions over the next weeks and months (Young et al., 1998b; Robertson et al., 2000). Juvenile material arrived at the surface around November 15th 1995 (Young et al., 1998b) building the first lava dome of the eruption. The eruption has been characterized by 1-2 years of lava effusion and associated dome growth interrupted by 1-2 year long or less periods of no extrusion. This pattern of eruption is in contrast to the quasi-continuous emissions of SO_2 throughout the eruption (Figure 2).

The effusive episodes are punctuated by pyroclastic flows generated by dome collapse or vulcanian explosions. Episodes of lava extrusion and dome growth at Soufrière Hills are referred to as phases (numbered I to V) while the periods of no magma production are referred to as pauses. During each period of extrusion, deformation and seismic activity correlates strongly with lava extrusion (Figure 3). The volcanic activity of phases I to V is described in detail elsewhere (e.g. Aspinall et al., 1998; Young et al., 1998b; Miller et al., 1998; Calder et al., 2002; Norton et al., 2002; Sparks & Young, 2002; Herd et al., 2005; Loughlin et al., 2010; Ryan et al., 2010; Wadge et al., 2010).

The first three phases of dome building were characterized by extended periods (on the order of 20 months) of extrusion and pause (Figures 1, 3). Phases IV and V were much shorter: phase IV was characterized by two separate episodes of low extrusion rates punctuated by explosions, the first in July-August 2008 and the second in December 2008-January 2009 (Komorowski et al., 2010). An approximate volume of 30 x10^6 m^3 of andesitic lava was erupted for each episode (Wadge et al., 2010). Phase V was also short lived (early October 2009 till mid February 2010), and was associated with the extrusion of ~ 70 x10^6 m^3 of lava. As was the case with phase IV, Phase V was characterized by sporadic explosive activity during extrusion (Stinton et al., in press).

METHODOLOGY FOR THE MEASUREMENT OF SULFUR DIOXIDE FLUX

From July 1995 till December 2001, intermittent SO_2 flux measurements were made with the correlation spectrometer (COSPEC) and have been presented elsewhere (e.g. Gardner et al., 1998, Young et al., 1998b). Traverses with the COSPEC under the plume were done by car, boat and helicopter. A detailed description of the COSPEC technique can be found in Stoiber et al. (1987) and Young et al. (2003). Subsequent to the COSPEC; miniature, low cost ultraviolet (UV) spectrometers were used to obtain SO_2 fluxes. The data are reduced using the Differential Optical Absorption Spectroscopy (DOAS) technique (Platt, 1994). Two automated and telemetered UV spectrometers, coupled with scanning devices, were installed on the western flanks of the Soufrière Hills volcano at Lovers Lane and Brodericks (Figure 2) and they collect spectra continuously during daylight hours, thus providing daily flux measurements with an estimated error of <35% (Galle et al., 2002; Edmonds et al., 2003a). Details of installation of the network, instrument specifications, spectral evaluation, mass flux calculation, associated errors and other information relating to the Soufrière Hills UV scanning network is described in detail by Edmonds et al. (2003a). The UV network provided a more robust and continuous dataset compared to the COSPEC and has produced a virtually continuous record of SO_2 fluxes for more than 10 years. It must be noted that the error varies on a daily basis in the measurements due to variable conditions and precision is more reliable than accuracy for the flux measurements.

THE SULFUR DIOXIDE FLUX TIME SERIES

Phases I & II / Pauses I & II

Initial degassing measurements were performed at the Soufrière Hills from July 29th 1995 to early September 1995 (Young et al, 1998a; Gardner and White, 2002). The measurements were carried out during the period of early phreatic activity in the eruption, prior to the onset of dome growth. SO_2 fluxes were 300 - 800 t/d and peaked at 1200 t/d on August 6th. The SO_2 emission rate shows a general increase from 1996 to 1997 during the first extrusion phase (Figure 1). The mean daily SO_2 flux during the first extrusion episode was 569 t/d. The highest measured daily output was 4150 t/d on July 13th 1998; this high value followed closely a large dome collapse which occurred on July 3rd 1998 (Norton et al., 2002; Edmonds et al., 2003b). The SO_2 flux showed an overall downward trend during the first pause period with a daily mean of 699 t/d, with a peak value of 4150 t/d occurring on July 13th 1998. From 1997 to mid 1999 (most of phase I and all of pause I), the SO_2 signal is generally defined by large pulsed signal over the duration (Figure 1).

The SO_2 flux during the Phase II also define pulse like signals over durations of years, the first from late 1999 to mid 2001 which peaked in late August – early September 2000, with a value of 2570 t/d (Figure 1). Another SO_2 pulse started in early 2002 and extends into the second pause period. The SO_2 flux during Phase II had a daily mean of 472 t/d. The SO_2 flux during Phase II peaked in early September 2000 (2570 t/d) after which the SO_2 flux decreased until around April 2001. This was followed by a general increase in SO_2 flux until the end of the extrusive episode in early August 2003 (Figure 1).

The mean daily SO_2 flux during the entire second pause was 562 t/d. The general increase in SO_2 flux that began during Phase II continued into the second pause period until early September 2003 when there was a general decreasing trend until June 2004. The mean daily flux from the start of the pause period until June 2004 was 696 t/d, after which the daily fluxes defined a fairly flat trend (~400 t/d), which continued until April 2005. The mean SO_2 flux over this month was 377 t/d. After April 2005, SO_2 flux began increase once again (up to 534 t/d) leading up to the onset of Phase III of lava extrusion (Figure 1). The peak SO_2 flux of the pause period (12,999 t/d) occurred on October 8th 2004, during the time when the mean daily flux for the month was otherwise 388 t/d. This is the highest daily mean flux measured during the eruption to date.

Phases III & IV / Pauses III, IV and V

The general trend of increasing SO_2 flux from the second pause, continued into Phase III. The SO_2 flux increased up to October 2005 to a maximum flux of 1522 t/d, after which it broadly decreased up until July 2006 after which another period of low flux values (~ 300 t/d) occurred and lasted until July 2007. The mean daily flux for the whole of Phase III is 440 t/d. The peak flux value during Phase III (3980 t/d), occurred on the last day of lava extrusion (April 4th 2007). It must be however noted that the mean daily flux for the first ten days of April 2007 was ~ 2000 t/d.

The SO_2 flux at the start of pause III were elevated over the eruption mean, however the flux decreased again and remained fairly low (274 t/d) until July 2007 when another general increase in the daily flux values began. This increasing trend in SO_2 flux continued until late May 2008; the mean daily flux during this period was 688 t/d. There was another trend of decreasing flux values from mid April 2008 till July 18th 2008, when the SO_2 flux was 412 t/d. This was followed by a significant elevation in the SO_2 flux over the next ten days (1100 t/d) that led up to the vulcanian explosion of July 29th 2008 that heralded the start of Phase IV a (Figures 1, 3).

The SO_2 flux remained elevated until early October 2008 when SO_2 flux again decreased with time, which continued throughout all of Phase IV a, IV b and their subsequent pauses (Figures 1, 3). This decreasing trend was brought to an end by the onset of Phase V when the activity incapacitated the spectrometer network with constant heavy ash fall. The mean daily flux from the onset of Phase IVa to the onset of Phase V is 675 t/d. The mean daily flux for Phase IVa is 923 t/d while the mean daily for Phase IV b is 451 t/d, which is consistent with a trend of waning daily flux. Flux measurements resumed in mid March 2010 and since then there has been no new lava production at the volcano (Figures 1, 3). The mean daily flux between March 17th 2010 and

August 31st 2010 was ~ 400 t/d and has remained fairly constant (+/- 281 t/d), (Figures 1, 3). Over the entire eruption, the mean daily SO_2 flux has been ~ 500 t/d.

The SO_2 flux time series clearly show three pulses on time scales of 1.5-3 years (Table 1). The amplitude of the pulses are (200-300 t/d) above the background of 300-400 t/d. The third and most recent pulse had a longer period and higher amplitude than the previous two. Pulses on this timescale appear to have ceased in early 2010, coincidental with the end of Phase V. The mean daily SO_2 output since then is similar to that of the periods intermediate between pulses. Superimposed on these pulses that lasts 2-3 years are shorter timescale variability in the SO_2 signal on the order of days to months which is less systematic and appears better correlated with other volanological phenomena such as lava extrusion and seismicity , volcano-tectonic (VT) earthquakes in particular, which have been occurring since 2007 in short intense bursts lasting less than 1 hour and are referred to as VT strings (Figure 4). VT strings are defined as a short intense swarm of VT earthquakes lasting less than one hour, occurring during a low background level of VT activity with four or more triggered events (Cole et al., 2010).

TIME SERIES ANALYSIS

Volcanic SO_2 flux time series typically contain error-induced noise that makes it difficult to recognize and constrain periodicities without a statistical analysis. The time series presented here also contains significant gaps that render statistical analysis by simple Fourier Transform methods non-effective. Degassing time series datasets obtained from volcanoes have been analyzed by wavelet analysis previously and have proven very useful in constraining periodicities in volatile fluxes that relate to episodic volatile delivery (e.g. Oppenheimer et al., 2009; Boichu et al., 2010).

$$\int_{-\infty}^{\infty} |\psi(t)|^2 \, dt = 1 \qquad (1)$$

Wavelet analysis decomposes a time series into time–frequency space, thus making it possible to determine both the dominant modes of variability and how those modes vary in time (Torrence & Compo, 1998). Wavelet transforms are mathematical techniques, based on group theory and square integrable representations, which allows unfolding of a signal into both space and scale, by using analyzing functions called wavelets, which are localized in space (Farge, 1992). A wavelet is a wave-like oscillation whose amplitude changes from zero to some maximum then back to zero, or in other words decays over a finite duration.

$$\int_{-\infty}^{\infty} \psi(t) dt = 0 \qquad (2)$$

This is mathematically achieved by imposing two restrictions on the wavelet function ψ (t). Equation (1) shows that the wavelet function must depart from zero for a limited duration while equation (2) requires a matching negative departure, thus creating a small wave. Generally, wavelets are crafted purposefully to have relevant properties that make them useful for processing a specific signal. The term wavelet function is generally used to refer to either orthogonal or nonorthogonal wavelets.

The nonorthogonal transform is useful for time series analysis, where smooth, continuous variations in wavelet amplitude are expected and hence this is the type of wavelet function employed in this study. A nonorthogonal wavelet function can be used with either the discrete or the continuous wavelet transform (CWT) (Farge 1992). Thus the continuous wavelet transform offers a continuous and redundant unfolding in terms of both space and scale.

$$\psi(t) = \pi^{-1/4} e^{i\omega 0t} e^{-t2} / 2 \qquad (3)$$

Wavelet transforms have the advantage of being able to analyze a time series with multiple embedded signals. A Morlet wavelet is a symmetrical (CWT), comprising of an exponential carrier wave modulated by a Gaussian function, equation (3). The Morlet wavelet has the added ability to distinguish components of a time series as they change with time at differing scales. The scale decomposition is obtained by dilating or contracting the chosen analyzing wavelet before convolving it with the signal (Farge 1992).

The limited spatial support of wavelets is important because then the behavior of the signal at infinity does not play any role. Therefore the wavelet analysis or syn-thesis can be performed locally on the signal, as opposed to the Fourier transform, which is inherently nonlocal due to the space-filling nature of the trigonometric functions (Farge 1992; Percival & Walden, 2000).

Wavelet results

The wavelet analysis was applied to the entire dataset after running the data through an 11-day median filter. Gaps in the time series were filled using random values from a population with the same standard deviation as the data. For the wavelet analysis of such a random series, white noise does not exhibit any cycles and hence produces gaps in the plot. The plots generated by the wavelet analysis (Figure 5) confirm that there are two cycles in excess of 50 days: one at ~ 4-5 months and the other in the range ~ 2-3 years, with both being present throughout the entire SO_2 time series and are independent of magma extrusion (Figures 1 & 6).

Nicholson et al. (2013) identified cyclicity on time scales on the order of 2-3 years, 6-8 weeks (50 days) and 10-14 days. Their Fourier Transform methods used for time series analysis differs somewhat from our own. The gaps less than 14 days in the dataset were filled using linear interpolation, however they employed reconstructive analysis methods to account for the larger gaps. And a Short term Fourier Transform (STFT) was employed; a sliding window of spectral snapshots over a specified duration, with each snapshot having varying degrees of overlap with its neighbors. Window lengths of 256-128 days and overlaps of 50% to 99% were used.

DISCUSSION

In this section we explore the controls on the 4-5 months and the ~ 2-3 year periodicity in the SO_2 time series. We consider shallow controls: changes in the degree of scrubbing of SO_2 from the gases on long cycles controlled by changes in the groundwater level or other hydrological factors; and changes in the shallow permeability of the conduit and lava dome (i.e. "open vent" conditions might promote high gas fluxes, the presence of a lava dome might subdue outgassing). We then consider deeper controls: the sulfur is thought to be linked ultimately to the supply of mafic magma at depth (e.g. Edmonds et al., 2001; 2010).

Models of ground deformation suggest there are two linked magma reservoirs, one at ~6 and one at ~12 km depth (Elsworth et al., 2008; Foroozan et al., 2010; Paulatto et al., 2010; Foroozan et al., 2011). Dual reservoirs feeding silicic volcanoes have been proposed elsewhere: Tomiya et al. (2010) put forward petrological evidence for a dual reservoir configuration beneath Mt Usu volcano in Japan. The depth at which the mafic magma interacts with the andesite is however not well constrained thus while the SO_2 flux at the surface may be a proxy for deep magma supply, there is likely to be a time lag for S-rich vapour to escape from the system through a large body of crystal-rich andesite.

During eruptive periods magmatic vapour is advected by upward-moving magma and augmented by syn-eruptive degassing, which can be clearly seen in the correlations between lava extrusion rate, seismicity and SO_2 flux recorded previously (e.g. Gardner and White, 1998; Young et al., 1998; Watson et al., 2000; Young et al., 2003; Nicholson et al., 2013). However, SO_2 outgassing during periods of no magma extrusion (pauses) are clearly not advected by moving magma. In this case it must migrate through a crystal-rich andesitic magma body to the surface.

We therefore investigate the characteristic time scales for a batch of gas to move through a large andesite magma body. We also explore the possibility that the mafic magma body is convecting at depth, and perturbations as a result of this convection might give rise to cyclic degassing. And lastly we explore the timescales of magma convection in a crystal-rich andesite using existing models (Kazahaya et al., 1994; Stevenson & Blake, 1998; Couch et al., 2001).

Metrological /Aquifer control

It has been shown that the abundance of SO_2 in volcanic plumes can be influenced by groundwater aquifer levels, the hydrothermal system and atmospheric humidity, in a process referred to as scrubbing (e.g. Doukas & Gerlach, 1992; Sutton et al., 1997; Symonds et al., 2001; Gerlach et al., 2002; Duffell et al., 2003; Werner et al., 2006; Rodriguez et al, 2008; Werner et al., 2012). Scrubbing involves the chemical interaction of SO_2 in the volcanic plume with water and oxygen, described in equations 4 and 5. The interaction of SO_2 with H_2O yields the hydrolysis reaction in equation 4, which results in the reduction of SO_2 and the formation of hydrosulfuric acid (H_2SO_3), an inherently weak acid. This can be further oxidized to form mild sulfuric acid (H_2SO_4) although this is slow process.

Scrubbing at the Soufrière Hills Volcano has been shown to account for SO_2 loss rates exceeding 10^{-3} s^{-1} (Oppenheimer et al., 1998), with a mean of 10^{-4} s^{-1} (Rodriguez et al., 2008). The spectrometers typically measure the plume within 5 minutes of the gas being emitted from the vent, and so using these loss rates we estimate that scrubbing might account for a typical underestimate of up to 70%of the SO_2 degassing from the vent (Rodriguez et al., 2008) .

The loss rate of SO_2 might vary between the wet and the dry season. The relative humidity is heavily dependent on the rainy season, which coincides with the Atlantic hurricane season and thus varies sub-annually. This variation in humidity through the year might explain the differences in loss rates obtained by the afore-mentioned studies (Oppenheimer et al., 1998; Rodriguez et al., 2008). Increased rainfall would thus act to lower the SO_2 abundance in the plume by scrubbing either in the subsurface hydrothermal system or in the atmosphere. Oppenheimer et al. (1998) performed their measurements, finding the highest loss rates, during the peak of the rainy season when the relative humidity would be highest for the year while Rodriguez et al. (2008) performed their measurements on ash-free plumes during the dry season.

$$SO_2 + H_2O = H_2SO_3 \qquad (4)$$

$$2\ H_2SO_3 + O_2 = 2\ H_2SO_4 \qquad (5)$$

SO_2 might also be removed prior to outgassing, in a subsurface hydrothermal system. Geochemical studies the early 1990s revealed the existence of a large hydrothermal/geothermal system in the entire southern portion of the island, beneath the Soufrière Hills volcano (Chiodini et al,. 1996). The hot springs in Soufrières (fumaroles) on the flanks of the volcano prior to the onset of the current eruption contained sulfate and chloride species, indicative of dissolution of magmatic gases into the water (Chiodini et al., 1996). Cold spring outputs on Montserrat are directly correlated with the groundwater levels. The rainy season coincides with the Atlantic hurricane season and thus the 5 month pulsation might be modulated by the change in rainfall. A comparison of the monthly output of two proximal springs over the same duration as the SO_2

dataset from the spectrometer network (Figure 7) shows no correlation between the datasets and we therefore reject control by the hydrothermal/geothermal system as a primary control on the SO_2 flux periodicity on 5 month timescales.

Dome-modulated gas storage or release

Dome collapses and explosions at the Soufrière Hills volcano are frequently accompanied by releases of large quantities of SO_2 (e.g. Herd et al., 2005; Carn & Prata, 2010; Komorowski et al., 2010). Lava domes may trap volatiles in the shallow plumbing system by loading the volcanic edifice, causing the closing of fractures around the volcanic conduit which inhibits volatile leakage, the effectiveness of which is dependent on the dome height and foot print (Woods and Huppert, 2003; Taisne & Jaupart, 2008). A wider and higher dome is more efficient at loading the edifice and thus acts to reduce SO_2 outgassing.

There is no detailed data regarding the width of the base of the lava dome; however the 1 km diameter crater puts constraints on the dome foot print, and there have been a number of occasions when the base of the dome has filled the entire crater, for example during extrusion phase II (late May 2002 till July 2003) and also in Phase III from February 2007 to April 2007 the dome had a volume of ~200 $x10^6$ m^3 which is the largest to date (Ryan et al., 2010; Wadge et al., 2010). The large dome persisted through the next pause period and through extrusive Phases IV and V, with a net volume of 38 x 10^6 m^3 of lava added to the dome during both episodes (Stinton et al., in press).

The dome height was >1000 m a.s.l on April 4th 2007 (Ryan et al., 2010) and has been consistently greater than this since, particularly during Phase V (Stinton et al., in press). The low SO_2 flux during late 2006 and early 2007 is consistent with a dome-modulated SO_2 signal. However, the dome has had a volume of ~ 200 x 10^6 m^3 and a height of > 1000 m a.s.l since 2007, yet another pulse of SO_2 occurred from June 2007 till Jan 2010, during a period when of one of the largest emplaced domes of the eruption was present in the crater (Wadge et al., 2010; Figure 8).

Thus the size of the lava dome may not be exerting a first order control on SO_2 flux. In mid-2003 the SO_2 flux was increasing contemporaneously with an increasing dome volume and height (Figure 8). The highest extrusion rates during the eruption occurred in early 2006 leading up to the May 20th 2006 collapse and also during Phase V. Both these periods coincide with a waning SO2 flux (Figure 9), which is contrary to what you would expect for a first order control since increased extrusion rates should enhance degassing at the surface. Conversely the general trend of increasing SO_2 fluxes observed between Phases III and IV occurred during a period of no lava extrusion. Thus as is the case with the dome volume, there is also no correlation between the SO_2 and andesite extrusion rate (Figure 9). We therefore propose that the 1.5-2.5 year pulses in the SO_2 signal are neither modulated by the lava dome or extrusion rate.

SO_2 origin and degassing timescales

Petrological work on the eruptive products of Phase I showed that the enclaves and mafic groundmass are indicative of the intrusion of mafic magma, which may trigger and fuel the eruption (e.g. Barclay et al., 1998; Murphy et al., 1998; Murphy et al., 2000; Devine et al., 2003). Melt inclusions hosted by plagioclase contain very little sulfur (Edmonds et al., 2001), certainly not enough to account for the large fluxes of SO_2 outgassing at the surface. Hence the andesite residing in the Soufrière Hills reservoir is thus thought to be in equilibrium with a significant exsolved gas phase (e.g. Anderson, 1975; Gerlach, 1994; Wallace, 2001; 2005; Edmonds et al., 2008; Wallace & Edmonds, 2011; Witham, 2011).

The intruding mafic magma almost certainly supplies heat and volatiles to the overlying andesite, by a process similar to either gas sparging (e.g. Bachman & Bergantz., 2006; 2008) where the gases act as a "defrosting" agent, transferring heat to the overlying silicic magma (e.g. Bachman & Bergantz., 2003), the development of volatile-rich melt plumes at the interface (.e.g. Philips & Woods, 2002) or during second boiling which is caused by quench crystallization at the basalt – andesite interface (e.g. Martin et al., 2006; Edmonds et al., in press).

There is evidence, from e.g. diffusion profiles in Fe-Ti oxides (Devine et al., 2003) and the preservation of the K_2O-rich heterogeneities interpreted to be due to mafic intrusion and diffusive mixing (Humphreys et al., 2010) that the time scale between intrusion, heating of the andesite, quench-driven degassing and eruption of the hybrid magmas is on the order of hours to months. Patterns of ground deformation (Figure 3) reflect the eruption of andesite at the surface (periods of deflation accompanying eruption) and recharge of mafic magma (inflation during eruptive pauses) (e.g. Voight et al., 1999; Elsworth et al., 2008; Foroozan et al., 2011). The SO_2 pulses do not exhibit a correlation with ground deformation (Figure 3) indicating that there is no first order control by the intrusion of magma at depth on the long cycles in the SO_2 flux at the surface.

CYCLIC ACTIVITY AT Soufrière Hills AND AT OTHER LAVA-DOME BUILDING ERUPTIONS

Cyclic lava extrusion and or degassing displaying periodicities on several different time scales is well documented at a number of different type of volcanoes (e.g. Denlinger & Hoblitt, 1999; Voight et al., 1999; Voight et al., 2000; Barmin et al., 2002; Harris & Neri, 2002; Sparks & Young, 2002; Lazute et al., 2004; Harris et al., 2005; Sweeney et al., 2008; Oppenheimer et al., 2009; Wadge et al., 2010; Melnik & Costa, in press) and pulsations in magma discharge rates appears to be characteristic of dome-building eruptions (Barmin et al., 2002).

Cyclic patterns in lava effusion and SO_2 emissions were evident from the onset of and has characterized the Soufrière Hills eruption (e.g. Miller et al., 1998; Young et al., 1998; Voight et al., 1998; 1999; Roberston et al., 2000; Lensky et al., 2008; Loughlin et al., 2010). For example, Voight et al. (1998) identified a 6–14 h inflation cycle caused by magma pressurization at shallow depths (< 0.6 km below the base of dome) during the first episode of dome building (Phase I), which was related to non-linear dynamics of magma flow with stick-slip flow (e.g. Denlinger & Hoblitt, 1999; Voight et al., 1999). Druit et al. (2002) reported cycles (10 hour mean) in the vulcanian explosions of 1997 at the Soufrière Hills.

Sparks & Young (2000) identified a 6 to 7 week magma extrusion cycle in 1997 while Loughlin et al. (2010) also showed that there was a two to six week pulsed signal in the magma discharge rate during Phase III. More recently in Phase V, magma delivery to the surface occurred in three major pulses ranging from 30-45 days duration (Stinton et al., in press), with sub-daily cycles on the order or 4-14 hours (Odbert et al., in press). Odbert et al., (in press) further showed that cyclic behavior at the Soufrière Hills volcano can range from sub-daily (hours) to muti-decadal. It is not uncommon to encounter multiple superimposed cycles hence a single explanation will not be satisfactory since multiple processes are likely involved (Costa et al., 2007). It has been shown by many recent studies that pulsed out flux can exist in a system with a constant influx of magma into a magma reservoir (Melnik & Sparks, 1999; Melnik & Sparks, 2002; Barmin et al., 2002, Melnik & Costa, in press).

A number of models exist that explain how the none-continuous delivery of lava to the surface throughout the Soufrière Hills eruption . The models employ the nonlinear effects of crystallization and gas loss which leads to rheological stiffening, and pressurization (e.g. Melnik & Sparks, 1999; Voight et al., 1999). Rheological stiffening increases magma overpressure (Melnik & Sparks, 2002), changes in magma pressure and crystallization kinetics causes a strong feedback mechanism and multiple steady solutions for discharge rate (Melnik & Sparks, 2002). Large changes in discharge rate and eruptive behavior can occur as the consequence of small changes in chamber pressure thus promoting none linear extrusion of magma at the surface (Melnik & Sparks, 2002). The system can thus fluctuate between low and high discharge rates at the surface (Melnik & Sparks, 2005).

Stick-slip magma flow in the upper conduit might result from degassing-induced changes in crystal content and hence bulk viscosity of the magma (Sparks & Young 2002; Sparks, 2003) When the magma overpressure drops to the dynamic strength of the slip surfaces, the plug sticks and blocks the vent thus initiating another episode of increasing magma pressure and another eruptive cycle (Lensky et al., 2008). Costa et al. (2007) porposed a model for the 6- 7 week cycles and attributed it to the elastic deformation of the dyke which connects the upper reservoir to a conduit that leads to the surface, the dyke behaves like a capacitor that deforms and stores magma eventually releasing it when the pressure increases to an optimum value.

Pulsed lava effusion is documented for the Mt St Helens (1980-1987) eruption and the Santiaguito (1922-2000) eruption. Barmin et al. (2002) used a mathematical model to describe the pulsatory behavior of Mt St Helens, which incorporates the non-linear response to magma extrusion to chamber pressure, owing to the changes in rheological properties and development of overpressures during degassing and ascent (Melnik and Sparks, 1999; Melnik and Sparks, 2002; Slezin, 2003). They showed that for a fixed chamber pressure, three different magma ascent velocities can occur. For a steady magma influx, decreases in conduit diameter, crystal growth rate and crystal number density in the magma can generate periodic behavior.

Elsworth et al. (2008) suggests a fairly steady and continuous influx of mafic magma into the lower reservoir with a flux rate in the range of (1.2-2.0) m^3s^{-1} (Foroozan et al., 2011; Melnik & Costa, in press). The short timescales between reheating and extrusion (e.g. Devine et al., 2003; Rutherford & Devine 2003) indicate that basalt influx into the andesite reservoir and the extrusion of andesite are correlated in time and likely occur for similar durations, this is consistent with the model of Melnik & Costa (in press) where influx of fresh magma into the andesite reservoir results in dome extrusion. The short term pulsations in the SO_2 signal, < 50 days (Nicholson et al., 2013) that can be correlated with seismic phenomena (e.g. Luckett et al., 2002; Norton et al., 2002; Loughlin et al., 2010) are likely driven by the shallower and smaller andesite reservoir.

The duration of the effusion phases have however decreased since 2007, suggesting variability in one or more parameters relevant for modulating oscillatory periods of the lava effusion. We did mention that the duration of the SO_2 pulses are similar to that of the first three extrusion episodes and the last pulse occurred just after the nature of the extrusion changed. It would thus be also fair to conclude that the durations of the initial three extrusion phases and the durations of the pulses in the SO_2 signal are not coincidental.

Reservoir connectivity model

Barmin et al. (2002) showed that lava extrusion rate can be variable at constant pressure in the andesite reservoir; however we have demonstrated that the SO_2 pulses are not being controlled by the andesite reservoir. Recent geophysical studies (e.g. Foroozan et al., 2010, Melnik & Costa, in press) have shown that the deformation signal which correlates with extrusion at the Soufrière Hills (Figure 3) can be attributed to both reservoirs. Melnik and Costa, (in press) assumed a steady influx into the deep chamber and used numerical modeling to show that both reservoirs are deforming and the level of connectivity between the two reservoirs are via an elastic dyke determines how much of an influence the deformation of the lower reservoir has on the signal at the surface at any time during the deformation cycle in Figure 3. Thus connectivity between the reservoirs at any point in time is dependent on the dyke width.

Variations in the connectivity of the reservoirs can also influence the pressure within each reservoir and the dyke. When the connectivity is weak the overpressure in the deep reservoir reaches high values (~ 70 MPa) and remains fairly constant during the cycle and the influx of fresh magma into the shallow reservoir is also nearly constant, high chamber overpressure influences the horizontal extension of the dyke and a consequent improvement of connectivity between two magma chambers. For a strong connectivity between the chambers their overpressures increases or decreases during the cycle in a synchronous way. Influx into the shallow chamber stays close to the extrusion rate at the surface.

Though the solubility of sulphur solubility is not mainly controlled by pressure (e.g. Scaillet et al., 1998; Scaillet & Pichavant, 2005) there is no petrological evidence indicating systematic changes in melt composition, temperature, fO_2 and fS_2 that correlate with the SO_2 pulses. We therefore propose that the (1.5- 2.5 year) pulses in SO_2 are related to localized pressure changes in the lower reservoir or dyke. The similarity in duration of the first three extrusion phases with the SO_2 pulses is consistent with the driving mechanism for both being similar.

Conclusions

We have used statistical techniques to demonstrate that like with magma production, there are pulsations in the SO_2 signal that vary on times scales of months to years. The pulses are however not correlated with extrusion which makes interpretation a bit tedious. We have however being able to rule out processes such as meteorological and aquifer control for controlling the SO_2 signal. We have also ruled out modulation by the lava dome. We therefore rely on the already established geophysical models of (Foroozan et al., 2010, Melnik & Costa, in press) which established the presence of two reservoirs and how they physically interact with each other given a certain degree of connectivity. We therefore embrace the model of (Melnik & Costa, in press) where pressure changes occur in the lower reservoir and connecting dyke that can influence sulfur solubility in the resident magma.

References

AIUPPA A., FEDERICO C., GIUDICE G., GIUFFRIDA G., GUIDA R., GURRIERI S., LIUZZO M., MORETTI R. & PAPALE P. 2009. The 2007 eruption of Stromboli volcano. Insights from real-time measurement of the volcanic gas plume CO2/SO2 ratio. *Journal of Volcanology and Geothermal Research*. **182**(3-4), 221-230.

ANDRES R.J., ROSE W.I., KYLE P.R., DESILVA S., FRANCIS P., GARDEWEG M. & MORENO ROA H. 1991. Excessive sulfur dioxide emissions from Chilean volcanoes. *Journal of Volcanology and Geothermal Research* **46** (3-4), 323-329.

ASPINALL W. P., MILLER A. D., LYNCH L. L., LATCHMAN J. L., STEWART R. C., WHITE, R. A & POWER J. A.1998. Soufrière Hills Eruption, Montserrat, 1995-1997. Volcanic earthquake locations and fault plane solutions. *Geophysical Research Letters* **25** (18), 3397-3400.

BACHMANN O.& BERGANTZ G.W. 2003. Rejuvenation of the Fish Canyon magma body: A window into the evolution of large-volume silicic magma systems 10.1130/G19764.1 *Geology* **31** (9), 789-792

BACHMANN O.& BERGANTZ G.W. 2006. Gas percolation in upper-crustal silicic crystal mushes as a mechanism for upward heat advection and rejuvenation of near-solidus magma bodies. *Journal of Volcanology and Geothermal Research* **149**(1-2), 85-102.

BACHMANN O.& BERGANTZ G.W. 2008. Deciphering Magma Chamber Dynamics from Styles of Compositional Zoning in Large Silicic Ash Flow Sheets. *Reviews in Mineralogy and Geochemistry* **69** (1), 651-674

BARCLAY J., RUTHERFORD M.J., CARROLL M.R., MURPHY M.D., DEVINE J.D., GARDNER J. & SPARKS, R.S.J. 1998. Experimental phase equilibria constraints on pre-eruptive storage conditions of the Soufriere Hills magma. *Geophysical Research Letters* **25**(18), 3437-3440.

BARCLAY J., HERD R. A., EDWARDS B. R., CHRISTOPHER T.E., KIDDLE E. J., PLAIL M. & DONOVAN A. 2010. Caught in the act: Implications for the increasing abundance of mafic enclaves during the recent eruptive episodes of the Soufrière Hills Volcano, Montserrat. *Geophysical Research Letters* **37**, L00E09, doi:10.1029/2010GL042509.

BARMIN A., MELNIK O. & SPARKS R.S.J. (2002). Periodic behavior in lava dome eruptions. *Earth and Planetary Science Letters* **199**(1-2), 173-184.

BLUTH G.J.S., CASADEVALL T.J., SCHNETZLER C.C., DOIRON S.D., WALTER L.S., KRUEGER A.J. & BADRUDDIN M. (1994). Evaluation of Sulfur-Dioxide Emissions from Explosive Volcanism - the 1982-1983 Eruptions of Galunggung, Java, Indonesia. *Journal of Volcanology and Geothermal Research* **63**(3-4), 243-256.

BOICHU M., OPPENHEIMER C., TSANEV V. & KYLE P.R. 2010. High temporal resolution SO2 flux measurements at Erebus volcano, Antarctica. *Journal of Volcanology and Geothermal Research* **190**(3-4), 325-336.

CALDER E.S., LUCKETT R., SPARKS R.S.J. & VOIGHT B. 2002. Mechanisms of lava dome instability and generation of rockfalls and pyroclastic flows at Soufrière Hills Volcano, Montserrat. *Geological Society, London, Memoirs* **21** (1), 173-190

CALTABIANO T., ROMANO R. & BUDETTA G.1994. SO2 flux measurements at Mount Etna (Sicily). *Journal of Geophysical Research*. **99**(D6), 12809-12819.

Carn S.A. & Prata F.J. 2010. Satellite-based constraints on explosive SO2 release from Soufriere Hills Volcano, Montserrat. *Geophysical Research Letters* **37**. doi: 10.1029/2010GL044971

CASADEVALL T., ROSE W., GERLACH T., GREENLAND L.P., EWERT J., WUNDERMAN R. & SYMONDS R. 1983. Gas Emissions and the Eruptions of Mount St. Helens through 1982. *Science* **221**(4618), 1383-1385.

CHIODINI G., CIONI R., FRULLANI A., GUIDI M., MARINI L., PRATI F. & RACO B. 1996. Fluid geochemistry of Montserrat Island, West Indies. *Bulletin of Volcanology* **58 (**380-392).

CHRISTOPHER T., EDMONDS M., HUMPHREYS M.C.S. & HERD R.A. 2010. Volcanic gas emissions from Soufriere Hills Volcano, Montserrat 1995-2009, with implications for mafic magma supply and degassing. *Geophysical Research Letters* **37**. L00E04, doi: 10.1029/2009GL041325.

CHRISTOPHER T., HUMPHREYS M.C.S., BARCLAY J., GENAREAU K., De ANGELIS S.M.H., PLAIL M. & DONOVAN A. 2012. Petrological and Geochemical Variation during the Soufrière Hills Eruption (1995-2010*). Geological Society of London Memoir*, eds. G. Wadge, R. Robertson, B. Voight, The eruption of Soufrière Hills Volcano, Montserrat from 2000 to 2010.

COLE P., BASS V., ELIGON C., MURREL C., ODBERT H., SMITH P., STEWART R., STINTON A., SYERS R., ROBERTSON R. & WILLIAMS P. Report to the Scientific Advisory Committee on Volcanic Activity at Soufriere Hills Volcano Montserrat. Report on Activity between 28 February 2010 and 31 October 2010 Open File Report OFR 10-02a

COSTA A., MELNIK O., SPARKS R.S.J. & VOIGHT B. 2007. Control of magma flow in dykes on cyclic lava dome extrusion. *Geophysical Research Letters* **34**(2). doi: 10.1029/2006GL027466

COUCH S., SPARKS R. & CARROLL M. 2001. Mineral disequilibrium in lavas explained by convective self-mixing in open magma chambers. *Nature* **411 (**1037-1039).

DENLINGER, R.P. & HOBLITT, R.P. 1999. Cyclic eruptive behavior of silicic volcanoes. *Geology* **27**(5), 459-462.

DEVINE J.D., RUTHERFORD M.J., NORTON G.E. & YOUNG S.R. 2003. Magma Storage Region Processes Inferred from Geochemistry of Fe - Ti Oxides in Andesitic Magma, Soufrière Hills Volcano, Montserrat, W.I. *Journal of Petrology* **44**(8), 1375-1400.

DOUKAS M.P. & GERLACH T. 1992. Sulfur dioxide scrubbing during the 1992 eruptions of Crater Peak, Mount Spurr volcano, Alaska. *The 1992 eruptions of Crater Peak vent, Mount Spurr volcano*, Alaska (ed. T. E. C. Keith). US Geol. Surv. Bull. **2139**, 47-57.

.

DRUITT T. H., YOUNG S. R., BAPTIE B., BONADONNA C., CALDER E. S., CLARKE A. B., COLE P. D., HARFORD C. L., HERD R. A., LUCKETT R., RYAN G. & VOIGHT, B. 2002. Episodes of cyclic Vulcanian explosive activity with fountain collapse at Soufriere Hills Volcano, Montserrat. *Geological Society, London, Memoirs* **21**(1). 281-306

EDMONDS M., PYLE D. & OPPENHEIMER C. 2001. A model for degassing at the Soufriere Hills Volcano, Montserrat, West Indies, based on geochemical data. *Earth and Planetary Science Letters* **186**(2), 159-173.

EDMONDS M., HERD R.A., GALLE B. & OPPENHEIMER C.M. 2003. Automated, high time-resolution measurements of SO_2 flux at Soufriere Hills Volcano, Montserrat. *Bulletin of Volcanology* **65**(8), 578-586.

EDMONDS M., OPPENHEIMER C., PYLE D.M., HERD R.A. & THOMPSON G. 2003. SO2 emissions from Soufriere Hills Volcano and their relationship to conduit permeability, hydrothermal interaction and degassing regime. *Journal of Volcanology and Geothermal Research* **124**(1-2), 23-43.

EDMONDS M., AIUPPA A., HUMPHREYS M., MORETTI R., GIUDICE G., MARTIN R.S., HERD R.A. & CHRISTOPHER T. 2010. Excess volatiles supplied by mingling of mafic magma at an andesite arc volcano. *Geochemistry Geophysics Geosystems* **11** (4). doi: 10.1029/2009GC002781

EDMONDS M., HUMPHREYS M.C.S., HARUI E., HERD R., WADGE G., RAWSON H., LEDDEN R., PLAIL M., BARCLAY J., AIUPPA A., CHRISTOPHER T., GIUDICE G. & GUIDA R. 2014. Pre-eruptive vapour and its role in controlling eruption style and longevity at Soufrière Hills Volcano. *Geological Society of London Memoir*, eds. G. Wadge, R. Robertson, B. Voight, The eruption of Soufrière Hills Volcano, Montserrat from 2000 to 2010.

ELSWORTH D., MATTIOLI G., TARON J., VOIGHT B. & HERD R. 2008. Implications of Magma Transfer Between Multiple Reservoirs on Eruption Cycling. *Science* **322 (**246-248)

FARGE M. (1992). Wavelet Transforms and Their Applications to Turbulence. *Annual Review of Fluid Mechanics* **24 (**395-457).
FICHAUT M., MARCELOT G. & CLOCCHIATTI R. 1989. Magmatology of Mt. Pelée (Martinique, F.W.I.). II: petrology of gabbroic and dioritic cumulates. *Journal of Volcanology and Geothermal Research* **38**(1-2), 171-187.

Fischer T.P., Morrissey M.M., Calvache M.L., Gomez D., Torres R., Stix J. & Williams S.N. 1994. Correlations between SO_2 Flux and Long-Period Seismicity at Galeras Volcano. *Nature* **368 (**135-137).

FOROOZAN R., ELSWORTH D., VOIGHT B. & MATTIOLI G.S. 2010. Dual reservoir structure at Soufriere Hills Volcano inferred from continuous GPS observations and heterogeneous elastic modeling. *Geophysical Research Letters* **37**. doi: 10.1029/2010GL042511.

FOROOZAN R., ELSWORTH D., VOIGHT B. & MATTIOLI G.S. 2011. Magmatic-metering controls the stopping and restarting of eruptions. *Geophysical Research Letters* **38**. L05306, doi: 10.1029/2010GL046591.

GALLE B., OPPENHEIMER C., GEYER A., MCGONIGLE A.J.S., EDMONDS M. & HORROCKS L. 2003. A miniaturised ultraviolet spectrometer for remote sensing of SO_2 fluxes: a new tool for volcano surveillance. *Journal of Volcanology and Geothermal Research* **119**(1-4), 241-254.

GARDNER C.A. & WHITE R.A. 2002. Seismicity, gas emission and deformation from 18 July to 25 September 1995 during the initial phreatic phase of the eruption of Soufrière Hills Volcano, Montserrat *Geological Society, London, Memoirs* **21** (1), 567-581

GERLACH T.M. & MCGEE K.A. 1994 Total sulfur dioxide emissions and pre-eruption vapor-saturated magma at Mount St. Helens, 1980-88. *Geophysical. Research. Letters* **21**(25), 2833-2836.

HARRIS A.J.L. & NERI M. 2002. Volumetric observations during paroxysmal eruptions at Mount Etna: pressurized drainage of a shallow chamber or pulsed supply? *Journal of Volcanology and Geothermal Research* **116**(1-2), 79-95.

HARRIS A., DEHN J., PATRICK M., CALVARI S., RIPEPE M. & LODATO L. 2005. Lava effusion rates from hand-held thermal infrared imagery: an example from the June 2003 effusive activity at Stromboli. *Bulletin of Volcanology* **68**(2), 107-117.

HERD R.A., EDMONDS M. & BASS V.A.2005. Catastrophic lava dome failure at Soufrière Hills Volcano, Montserrat, 12-13 July 2003. *Journal of Volcanology and Geothermal Research* **148** (3-4), 234-252.

HIRABAYASHI J., OHBA T., NOGAMI K. & YOSHIDA M. 1995. Discharge Rate of SO_2 from Unzen Volcano, Kyushu, Japan. *Geophysical Research Letters* **22**(13), 1709-1712.

HUMPHREYS M.C.S., CHRISTOPHER T. & HARDS V. 2009. Microlite transfer by disaggregation of mafic inclusions following magma mixing at SoufriSre Hills volcano, Montserrat. *Contributions to Mineralogy and Petrology* **157**(5), 609-624.

HUMPHREYS M.C.S., EDMONDS M., CHRISTOPHER T. & HARDS V. 2009. Chlorine variations in the magma of Soufriere Hills Volcano, Montserrat: Insights from Cl in hornblende and melt inclusions. *Geochimica Et Cosmochimica Acta* **73**(19), 5693-5708.

HUMPHREYS M.C.S., EDMONDS M., BARCLAY J., PLAIL M., PARKES D. & CHRISTOPHER T. 2012. A new method to quantify the real supply of mafic components to a hybrid andesite. Contributions to Mineralogy and Petrology 65 (1) 191-215

KARLSTROM L., DUFEK J. & MANGA M. 2010. Magma chamber stability in arc and continental crust. *Journal of Volcanology and Geothermal Research* **190**(3-4), 249-270.

KAZAHAYA K., SHINOHARA H. & SAITO G. (1994). Excessive Degassing of Izu-Oshima Volcano Magma Convection in a Conduit. *Bulletin of Volcanology* **56**(3), 207-216.

KENT A.J.R., DARR C., KOLESZAR A.M., SALISBURY M.J. & COOPER K.M. 2010. Preferential eruption of andesitic magmas through recharge filtering. **3**(9), 631-636.

KOMOROWSKI J.C., LEGENDRE Y., CHRISTOPHER T., BERNSTEIN M., STEWART R., JOSEPH E., FOURNIER N., CHARDOT L., FINIZOLA A., WADGE G., SYERS R., WILLIAMS C. & BASS V. 2010. Insights into processes and deposits of hazardous vulcanian explosions at Soufriere Hills Volcano during 2008 and 2009 (Montserrat, West Indies). *Geophysical Research Letters* **37**. L00E19, doi: 10.1029/2010GL042558.

KRESS V. 1997. Magma mixing as a source for Pinatubo sulphur. **389**(6651), 591-593.

LAUTZE N.C., HARRIS A.J.L., BAILEY J.E., RIPEPE M., CALVARI S., DEHN J., ROWLAND S.K. & Evans-Jones K. 2004. Pulsed lava effusion at Mount Etna during 2001. *Journal of Volcanology and Geothermal Research* **137**(1-3): 231-246.

LENSKY N.G., SPARKS R.S.J., NAVON O. & LYAKHOVSKY V. 2008. Cyclic activity at Soufrière Hills Volcano, Montserrat: degassing-induced pressurization and stick-slip extrusion *Geological Society, London, Special Publications* **307** (1), 169-188

LINDE A.T., SACKS S., HIDAYAT D., VOIGHT B., CLARKE A., ELSWORTH D., MATTIOLI G., MALIN P., SHALEV E., SPARKS S. & WIDIWIJAYANTI C. 2010. Vulcanian explosion at Soufrière Hills Volcano, Montserrat on March 2004 as revealed by strain data. *Geophysical Research Letters* **37**(19), L00E07.

LOUGHLIN S.C., LUCKETT R., RYAN G., CHRISTOPHER T., HARDS V., De ANGELIS S., JONES L. & STRUTT M. 2010. An overview of lava dome evolution, dome collapse and cyclicity at Soufrière Hills Volcano, Montserrat, 2005 -2007. *Geophysical. Research. Letters*. **37**: L00E16. doi: 10.1029/2010GL042547

LUCKETT R., BAPTIE B. & NEUBERG J. 2002. The relationship between degassing and rockfall signals at Soufriere Hills Volcano, Montserrat. *Geological Society, London, Memoirs* **21**(1), 595-602.

MARTEL C., RADADI Ali, A., POUSSINEAU S., GOURGAUD A. & PICHAVANT M. 2006. Basalt-inherited microlites in silicic magmas: Evidence from Mount Pelée (Martinique, French West Indies) *Geology* **34**(11): 905-908.

MARTIN V.M., HOLNESS M.B. & PYLE D.M. 2006. Textural analysis of magmatic enclaves from the Kameni Islands, Santorini, Greece. *Journal of Volcanology and Geothermal Research* **154**(1-2), 89-102.

MCGEE K.A. & SUTTON, A.J. 1994. Eruptive activity at Mount St Helens, Washington, USA, 1984-1988: a gas geochemistry perspective. *Bulletin of Volcanology*, **56 (**435-446).

MCGONIGLE A.J.S., OPPENHEIMER C., HAYES A.R., GALLE B., EDMONDS M., CALTABIANO T., SALERNO G., BURTON M. & MATHER T.A. 2003. Sulphur dioxide fluxes from Mount Etna, Vulcano, and Stromboli measured with an automated scanning ultraviolet spectrometer. *Journal of Geophysical Research: Solid Earth* **108**(B9): 2455.

MELNIK O. & COSTA A. 2014. Dual chamber-conduit models of non-linear dynamics behaviour at Soufrière Hills Volcano, Montserrat. *Geological Society of London Memoir*, eds. G. Wadge, R. Robertson, B. Voight, The eruption of Soufrière Hills Volcano, Montserrat from 2000 to 2010.

MELNIK O. & SPARKS R.S.J. 1999. Nonlinear dynamics of lava dome extrusion *Nature* **402 (**37-41) doi:10.1038/46950

MELNIK O. & SPARKS R.S.J. 2002. Dynamics of magma ascent and lava extrusion at Soufrière Hills Volcano, Montserrat. *Geological Society, London, Memoirs* **21**(1), 153-171.

MELNIK O. & SPARKS R.S.J. 2005. Controls on conduit magma flow dynamics during lava dome building eruptions. *Journal of Geophysical Research: Solid Earth* **110**(B2): B02209.

MILLER A.D., STEWART R.C., WHITE R.A., LUCKETT R., BAPTIE B.J., ASPINALL W.P., LATCHMAN J.L., LYNCH L.L. & VOIGHT B. 1998. Seismicity associated with dome growth and collapse at the Soufriere Hills Volcano, Montserrat. *Geophysical. Research. Letters*. **25**(18), 3401-3404.

MORETTI, R. & PAPALE, P. 2004. On the oxidation state and volatile behavior in multicomponent gas -melt equilibria. *Chemical Geology* **213**(1-3), 265-280.

MURPHY M.D., SPARKS R.S.J., BARCLAY J., CARROLL M.R. & BREWER T.S. 2000. Remobilization of andesite magma by intrusion of mafic magma at the Soufriere Hills Volcano, Montserrat, West Indies. *Journal of Petrology* **41**(1), 21-42.

MURPHY M.D., SPARKS R.S.J., BARCLAY J., CARROLL M.R., LEJEUNE A.M., BREWER T.S., MACDONALD R., BLACK S. & YOUNG S. (1998). The role of magma mixing in triggering the current eruption at the Soufriere Hills volcano, Montserrat, West Indies. *Geophysical Research Letters* **25**(18): 3433-3436.

Nicholson E.J., Mather T.A., Pyle D.M., Odbert H.M. & Christopher T. 2013. Cyclical patterns in volcanic degassing revealed by SO2 flux timeseries analysis: An application to Soufrière Hills Volcano, Montserrat. *Earth and Planetary Science Letters* **375** (0), 209-221.

NORTON G.E., WATTS R.B., VOIGHT B., MATTIOLI G.S., HERD R.A., YOUNG S.R., DEVINE G.E., ASPINNALL W.P., BONADONNA C., BAPTIE B.J., EDMONDS M., JOLLY A.D., LOUGHLIN S.C., LUCKETT R. & SPARKS S.J. 2002. Pyroclastic flow and explosive activity at Soufriere Hills Volcano, Montserrat, during a period of virtually no magma extrusion (March 1998 to November 1999) *Geological Society, London, Memoirs* **21**(1), 467-481.

ODBERT H.M., STEWART R.C & WADGE G. 2014. Cyclic phenomena at Soufriere Hills Volcano, Montserrat. *Geological Society of London Memoir*, eds. G. Wadge, R. Robertson, B. Voight, The eruption of Soufrière Hills Volcano, Montserrat from 2000 to 2010.

OHBA T., HIRABAYASHI J., NOGAMI K., KUSAKABE M. & YOSHIDA M. 2008. Magma degassing process during the eruption of Mt. Unzen, Japan in 1991 to 1995: Modeling with the chemical composition of volcanic gas. *Journal of Volcanology and Geothermal Research Scientific drilling at Mount Unzen* **175**(1-2), 120-132.

OPPENHEIMER C., FRANCIS P. & STIX J. 1998. Depletion rates of sulfur dioxide in tropospheric volcanic plumes. *Geophysical Research Letters* **25**(14), 2671-2674.

OPPENHEIMER C., LOMAKINA A.S., KYLE P.R., KINGSBURY N.G. & BOICHU M. 2009. Pulsatory magma supply to a phonolite lava lake. *Earth and Planetary Science Letters* **284**(3-4), 392-398.

PAULATTO M., ANNEN C., HENSTOCK T.J., KIDDLE E.J., MINSHULL T.A., SPARKS R.S.J. & VOIGHT B. 2011. Magma chamber properties from integrated seismic tomography and thermal modeling at Montserrat.*Geochemistry Geophysics Geosystems* **13** (1), doi:10.1029/2011GC003892

PAULATTO M., MINSHULL T.A., BAPTIE B., DEAN S., HAMMOND J.O.S., HENSTOCK T., KENEDI C.L., KIDDLE E.J., MALIN P., PEIRCE C., RYAN G., SHALEV E., SPARKS R.S.J. & VOIGHT B. 2010. Upper crustal structure of an active volcano from refraction/reflection tomography, Montserrat, Lesser Antilles *Geophysical Journal International* **180** (2): 685-696

Percival D. & Walden A. 2000. Wavelet Methods for Time Series Analysis (Cambridge Series in Statistical and Probabilistic Mathematics), Cambridge University Press.

PHILLIPS J.C. & WOODS A.W. 2002. Suppression of large-scale magma mixing by melt-volatile separation. Earth and Planetary Science Letters **204**(1-2), 47-60.

PLAIL M., BARCLAY J., HUMPHREYS M.C.S., EDMONDS M., HERD R.A. & CHRISTOPHER T. 2012. Characterisation of mafic enclaves in the erupted products of Soufrière Hills Volcano, Montserrat 1995-2010. *Geological Society of London Memoir*, eds. G. Wadge, R. Robertson, B. Voight, The eruption of Soufrière Hills Volcano, Montserrat from 2000 to 2010.

PLATT U. 1994. Differential optical absorption spectroscopy (DOAS). *Air Monitoring by Spectroscopic Technique* **127**: 27-84.

ROBERTSON R.E.A., ASPINALL W.P., HERD R.A., NORTON G.E., SPARKS R.S.J. & YOUNG S.R. 2000. The 1995-1998 eruption of the Soufriere Hills volcano, Montserrat, WI. *Philosophical Transactions of the Royal Society of London Series a-Mathematical Physical and Engineering Sciences* **358**(1770), 1619-1637.

RODRIGUEZ L.A., WATSON I.M., EDMONDS M., RYAN G., HARDS V., OPPENHEIMER C.M.M. & BLUTH G.J.S. 2008. SO2 loss rates in the plume emitted by Soufriere Hills volcano, Montserrat. *Journal of Volcanology and Geothermal Research* **173**(1-2), 135-147.

Ruprecht, P. and Plank, T. (2013). "Feeding andesitic eruptions with a high-speed connection from the mantle." **500**(7460): 68-72.

RUTHERFORD M.J. & DEVINE J.D. 2003. Magmatic Conditions and Magma Ascent as Indicated by Hornblende Phase Equilibria and Reactions in the 1995-2002 Soufrière Hills Magma. *Journal of Petrology* **44**(8), 1433-1453.

RYAN G.A., LOUGHLIN S.C., JAMES M.R., JONES L.D., CALDER E.S., CHRISTOPHER T., STRUTT M.H. & WADGE G. 2010. Growth of the lava dome and extrusion rates at Soufriere Hills Volcano, Montserrat, West Indies: 2005-2008. *Geophysical Research Letters* **37**. L00E08, doi: 10.1029/2009GL041477.

SATO H., NAKADA S., FUJII T., NAKAMURA M. & SUZUKI-KAMATA K. 1999. Groundmass pargasite in the 1991-1995 dacite of Unzen volcano: phase stability experiments and volcanological implications. *Journal of Volcanology and Geothermal Research* **89**(1-4), 197-212.

SATO H., HOLTZ F., BEHRENS H., BOTCHARNIKOV R. & NAKADA S. 2005. Experimental Petrology of the 1991-1995 Unzen Dacite, Japan. Part II: Cl/OH Partitioning between Hornblende and Melt and its Implications for the Origin of Oscillatory Zoning of Hornblende Phenocrysts. *Journal of Petrology* **46**(2), 339-354.
Scaillet B. & Pichavant M. 2005. A model of sulphur solubility for hydrous mafic melts: application to the determination of magmatic fluid compositions of Italian volcanoes. *Annals of Geophysics*. **48** (4-5) 671-698.

Scaillet B., Clemente B., Evans B.W. & Pichavant M. 1998. Redox control of sulfur degassing in silicic magmas. *Journal of Geophysical Research*. **103**(B10): 23937-23949.

SHINOHARA H. 2008. Excess Degassing from Volcanoes and Its Role on Eruptive and Intrusive Activity. *Reviews of Geophysics* **46**(4). doi:10.1029/2007RG000244.

SHINOHARA H., OHBA T., KAZAHAYA K. & TAKAHASHI H. 2008. Origin of volcanic gases discharging from a cooling lava dome of Unzen volcano, Japan. *Journal of Volcanology and Geothermal Research* **175**(1-2), 133-140.

SPARKS R.S.J. & YOUNG S.R. 2002. The eruption of Soufriere Hills Volcano, Montserrat (1995-1999): overview of scientific results. *Geological Society, London, Memoirs* **21**(1), 45-69.

SPARKS R.S.J. 2003. Dynamics of magma degassing. *Geological Society, London, Special Publications.* **213**(1). 5-22

STEVENSON, D.S. & BLAKE, S. 1998. Modelling the dynamics and thermodynamics of volcanic degassing. *Bulletin of Volcanology* **60**(4), 307-317.

STINTON A.J., COLE P.D., ODBERT H.M., CHRISTOPHER T.E., AVARD G. & BERNSTEIN M. 2014. Evolution of the Soufrière Hills volcano during a short, intense episode of dome growth: 4 October 2009 - 11 February 2010. *Geological Society of London Memoir*, eds. G. Wadge, R. Robertson, B. Voight, The eruption of Soufrière Hills Volcano, Montserrat from 2000 to 2010.

STOIBER R.E., WILLIAMS S.N. & HUEBERT B. 1987. Annual contribution of sulfur dioxide to the atmosphere by volcanoes. *Journal of Volcanology and Geothermal Research* **33**(1-3), 1-8.

SWEENEY D., KYLE P.R. & OPPENHEIMER C. 2008. Sulfur dioxide emissions and degassing behavior of Erebus volcano, Antarctica. *Journal of Volcanology and Geothermal Research* **177**(3), 725-733.

TAISNE B. & JAUPART C. 2008. Magma degassing and intermittent lava dome growth. Geophysical Research Letters **35**(20). L20310, doi: 10.1029/2008GL035432.

TOMIYA A., TAKAHASHI E., FURUKAWA N. & SUZUKI T. 2010. Depth and Evolution of a Silicic Magma Chamber: Melting Experiments on a Low-K Rhyolite from Usu Volcano, Japan. *Journal of Petrology* **51** (6), 1333-1354

TORRENCE C. & COMPO G.P. 1998. A Practical Guide to Wavelet Analysis. *Bulletin of the American Meteorological Society* **79**(1), 61-78.

VOIGHT B., CONSTANTINE E.K., SISWOWIDJOYO S. & TORLEY, R. 2000. Historical eruptions of Merapi Volcano, Central Java, Indonesia, 1768-1998. *Journal of Volcanology and Geothermal Research* **100**(1-4), 69-138.

VOIGHT B., HOBLITT R. P., CLARKE A. B., LOCKHART A. B., MILLER A. D., LYNCH L. & MCMAHON J. 1998. Remarkable cyclic ground deformation monitored in real-time on Montserrat, and its use in eruption forecasting. *Geophysical Research Letters* **25** (18) 3405-3408 doi: 10.1029/98GL01160

VOIGHT B., SPARKS R.S.J., MILLER A.D., STEWART R.C., HOBLITT R.P., CLARKE A., EWART J., ASPINALL W.P., BAPTIE B., CALDER E.S., COLE P., DRUITT T.H., HARTFORD C., HERD R.A., JACKSON P., LEJEUNE A.M., LOCKHART A.B., LOUGHLIN S.C., LUCKETT R., LYNCH L., NORTON G.E., ROBERTSON R., WATSON I.M., WATTS R. & YOUNG S.R. 1999. Magma flow instability and cyclic activity at Soufriere Hills Volcano, Montserrat, British West Indies. *Science* **283**(5405), 1138-1142.

WADGE G., HERD R., RYAN G., CALDER E.S. & KOMOROWSKI J.C. 2010. Lava production at Soufriere Hills Volcano, Montserrat: 1995-2009. *Geophysical Research Letters* **37**. L00E03, doi:10.1029/2009GL041466.

WALLACE P.J. 2001. Volcanic SO_2 emissions and the abundance and distribution of exsolved gas in magma bodies. *Journal of Volcanology and Geothermal Research* **108**(1-4), 85-106.

WALLACE P.J. 2005. Volatiles in subduction zone magmas: concentrations and fluxes based on melt inclusion and volcanic gas data. *Journal of Volcanology and Geothermal Research* **140**(1-3), 217-240.

WALLACE P.J. & GERLACH T.M. 1994. Magmatic Vapor Source for Sulfur Dioxide Released During Volcanic Eruptions: Evidence from Mount Pinatubo. *Science* **265** (497-499).

WALLACE P.J. & EDMONDS M. 2011. The Sulfur Budget in Magmas: Evidence from Melt Inclusions, Submarine Glasses, and Volcanic Gas Emissions. *Reviews in Mineralogy and Geochemistry* **73** (1), 215-246

WATSON I.M., OPPENHEIMER C., VOIGHT B., FRANCIS P., CLARKE A., STIX J., MILLER A., PYLE D.M., BURTON M.R., YOUNG S.R., NORTON G., LOUGHLIN S., DARROUX B. & STAFF M.V.O. 2000. The relationship between degassing and ground deformation at Soufriere Hills Volcano, Montserrat. *Journal of Volcanology and Geothermal Research* **98**(1-4), 117-126.

WERNER C., CHRISTENSON B.W., HAGERTY M. & BRITTEN K. 2006. Variability of volcanic gas emissions during a crater lake heating cycle at Ruapehu Volcano, New Zealand. *Journal of Volcanology and Geothermal Research* **154**(3-4), 291-302.

WERNER C., EVANS W.C., KELLY P.J., MCGIMSEY R., PFEFFER M., DOUKAS M. & NEAL C. 2012. Deep magmatic degassing versus scrubbing: Elevated CO_2emissions and C/S in the lead-up to the 2009 eruption of Redoubt Volcano, Alaska. *Geochemistry, Geophysics, Geosystems* **13**(3), doi: 10.1029/2011GC003794.

WERNER C., KELLY P.J., DOUKAS M., LOPEZ T., PFEFFER M., MCGIMSEY R. & NEAL C. 2013. Degassing of CO_2, SO_2, and H_2S associated with the 2009 eruption of Redoubt Volcano, Alaska. *Journal of Volcanology and Geothermal Research* **259**(0), 270-284.

WESTRICH, H.R. & GERLACH, T.M. (1992). Magmatic gas source for the stratospheric SO2 cloud from the June 15,1991, eruption of Mount Pinatubo. *Geology* **20** (10), 867-870

WITHAM F. 2011. Conduit convection, magma mixing, and melt inclusion trends at persistently degassing volcanoes. *Earth and Planetary Science Letters* **301**(1-2), 345-352.

YOUNG S.R., VOIGHT B. & DUFFELL H.J. 2003. Magma extrusion dynamics revealed by high-frequency gas monitoring at Soufriere Hills Volcano, Montserrat. *Volcanic Degassing* **213** (219-230).

YOUNG S.R., SPARKS R.S.J., ASPINALL W.P., LYNCH L.L., MILLER A.D., ROBERTSON R.E.A. & SHEPHERD J.B. 1998. Overview of the eruption of Soufriere Hills Volcano, Montserrat, 18 July 1995 to December 1997. *Geophysical Research. Letters* **25**(18), 3389-3392.

YOUNG S.R., FRANCIS P.W., BARCLAY J., CASADEVALL T.J., GARDNER C.A., DARROUX B., DAVIES M.A., DELMELLE P., NORTON G.E., MACIEJEWSKI A.J.H., OPPENHEIMER C.M.M., STIX J. & WATSON I.M. (1998). Monitoring SO_2 emission at the Soufriere Hills Volcano: Implications for changes in eruptive conditions. *Geophysical. Research. Letters* **25**(19), 3681-3684.

ZELLMER G.F., SPARKS R.S.J., HAWKESWORTH C.J. & WIEDENBECK, M. 2003. Magma Emplacement and Remobilization Timescales Beneath Montserrat: Insights from Sr and Ba Zonation in Plagioclase Phenocrysts. *Journal of Petrology* **44**(8), 1413-1431.

ZOBIN V.M., VARLEY N.R., GONZÁLEZ M., OROZCO J., REYES G.A., NAVARRO C. & BRETÓN M. 2008. Monitoring the 2004 andesitic block-lava extrusion at Volcan de Colima, Mexico from seismic activity and SO_2 emission. *Journal of Volcanology and Geothermal Research* **177**(2), 367-377.

Tables

Pulse/Int	Mean flux t/d	# of values	% Data Obtained	Approximate duration/ yrs
1st Int (June 2004 – April 2005)	427	250	69	0.99
2nd Int (Jul 2006 – Jul 2007)	304	317	92	0.94
1st pulse (June 2002 – May 2004)	561	625	86	2
2nd pulse (April 2005 – Jul 2006)	560	435	76	1.58
3 rd pulse (Jul 2nd 2007 - Jan 2010)*	664	732	87	2.31
2010 restart (mid march) - present	401	1040	82	3.47

Table 1 Break down of the relevant parameters of the pulses and intermediate periods that were observed in the uv network data. * denotes pulse where data was lost due to ash from Phase V

Figures

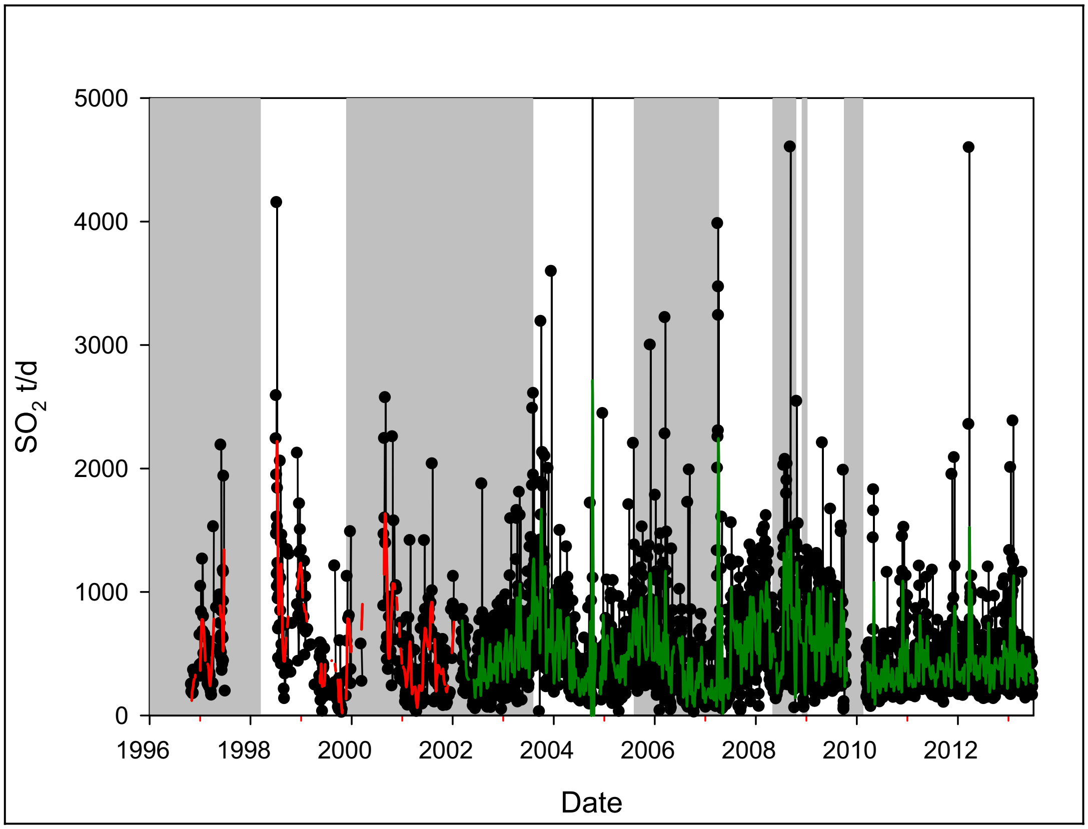

Figure 1 The Entire SO_2 time series showing continuous and variable SO_2 output throughout the eruption. Red line is 11 day filter though the COSPEC data and green line if 11 day filter through the spectrometer network data.

Figure 2 Google Earth image of southern Montserrat showing the location of the two network spectrometers relative to the volcano. The spectrometers are named based on their location (LL – Lovers lane, BR – Brodericks) . The prevailing winds are easterlies which normally puts the plume over Plymouth. In this image the plume is to the north of the network.

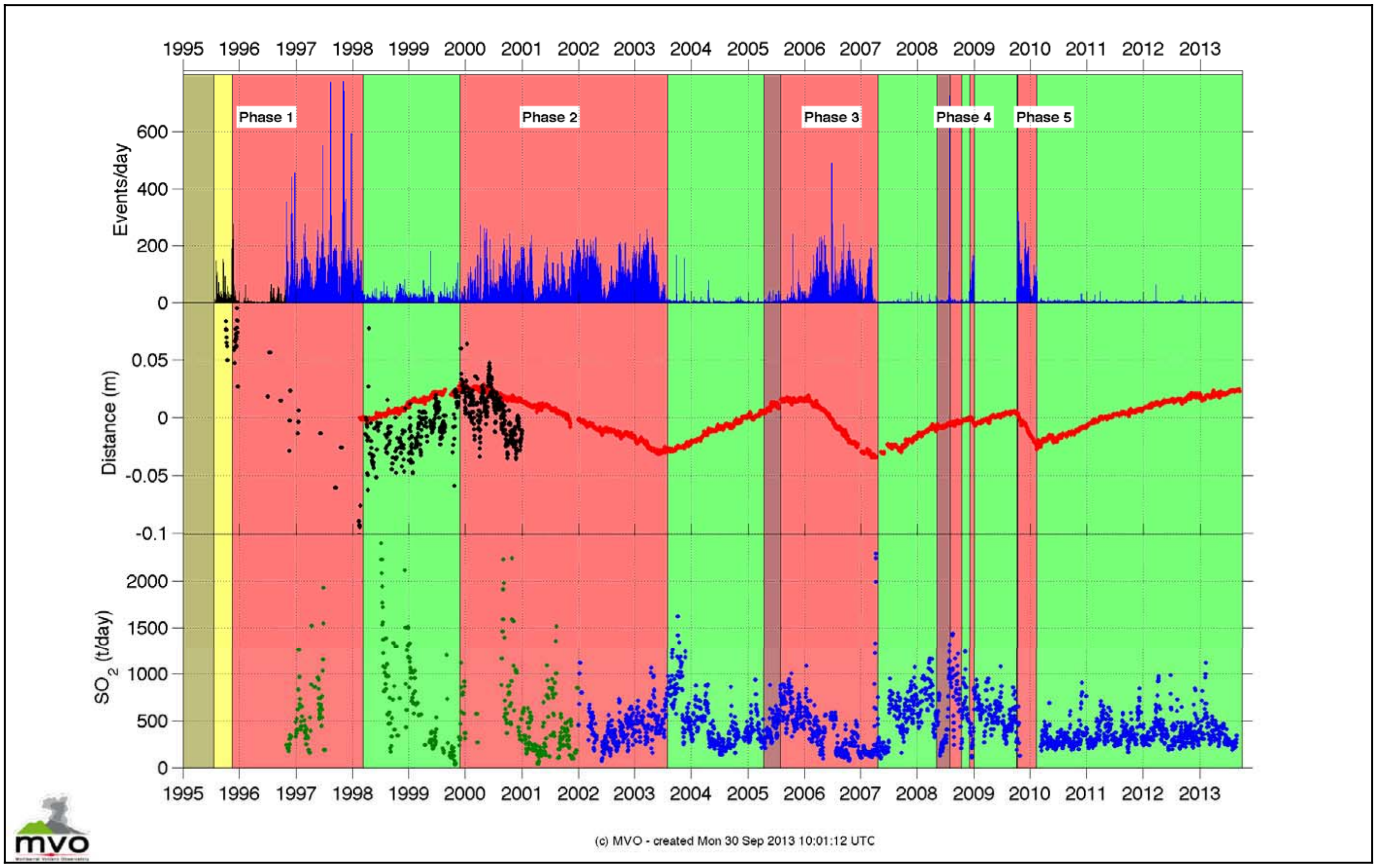

Figure 3 Multi-plot diagram used by the MVO showing how the seismic (top), deformation (middle) and SO2 varied throughout the whole eruption

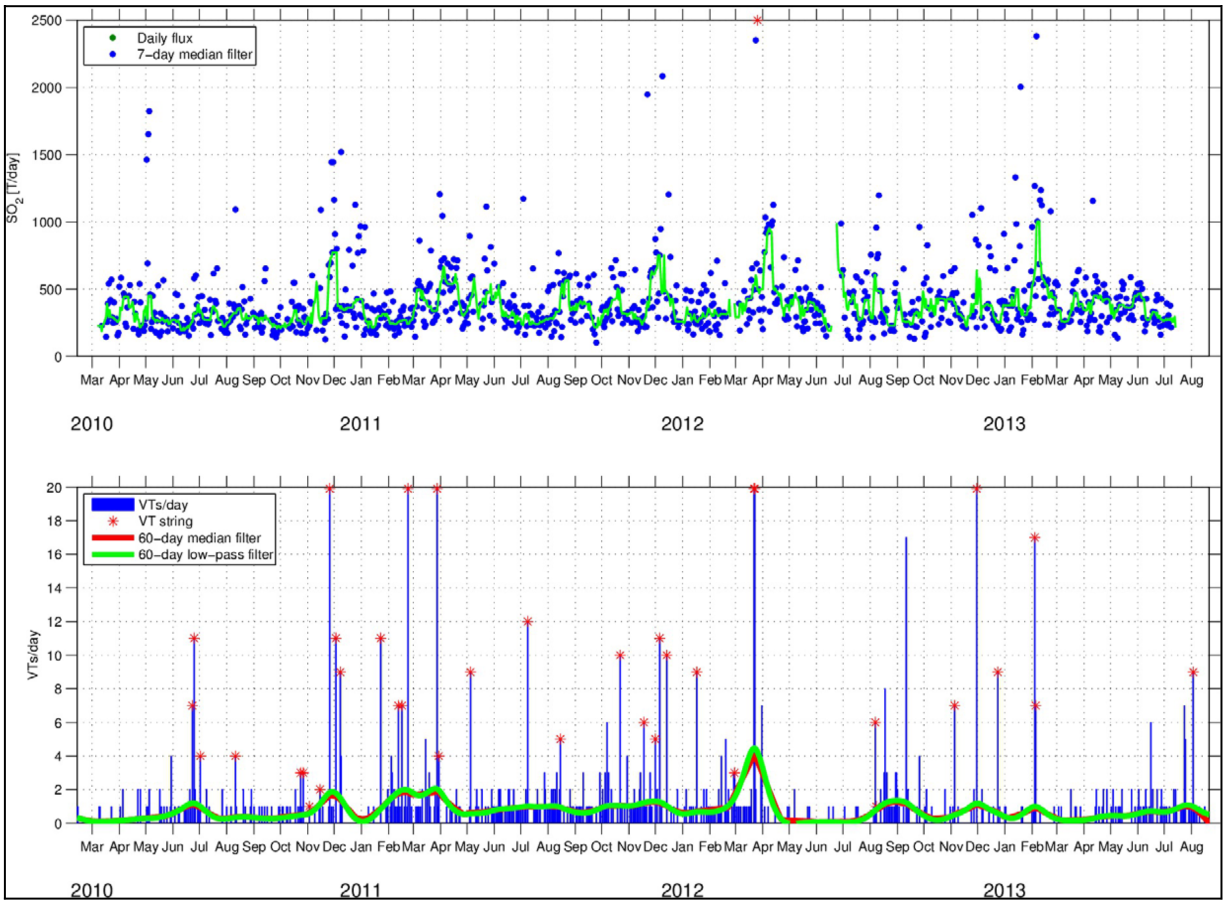

Figure 4 A comparison of mean daily post Phase V SO_2 flux values with VT earthquakes showing a fairly good correlation

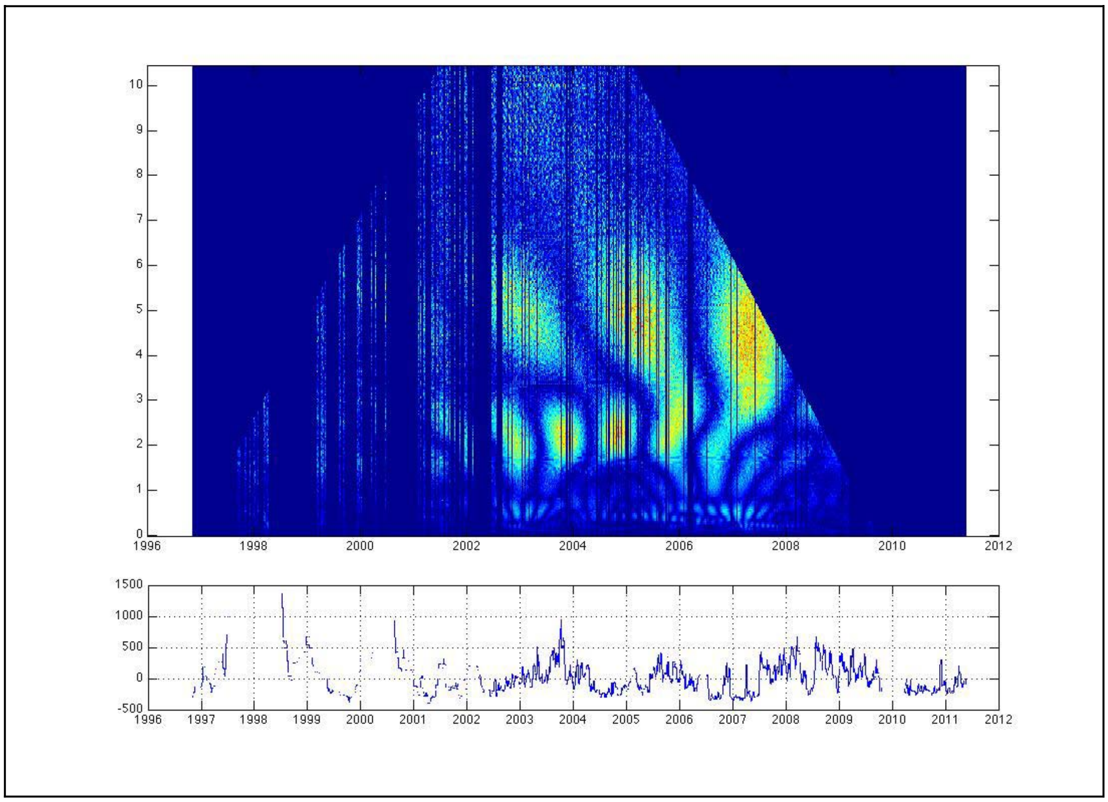

Figure 5 wavelet plot of the whole SO_2 dataset showing the ~ 2 year signal in the time series.

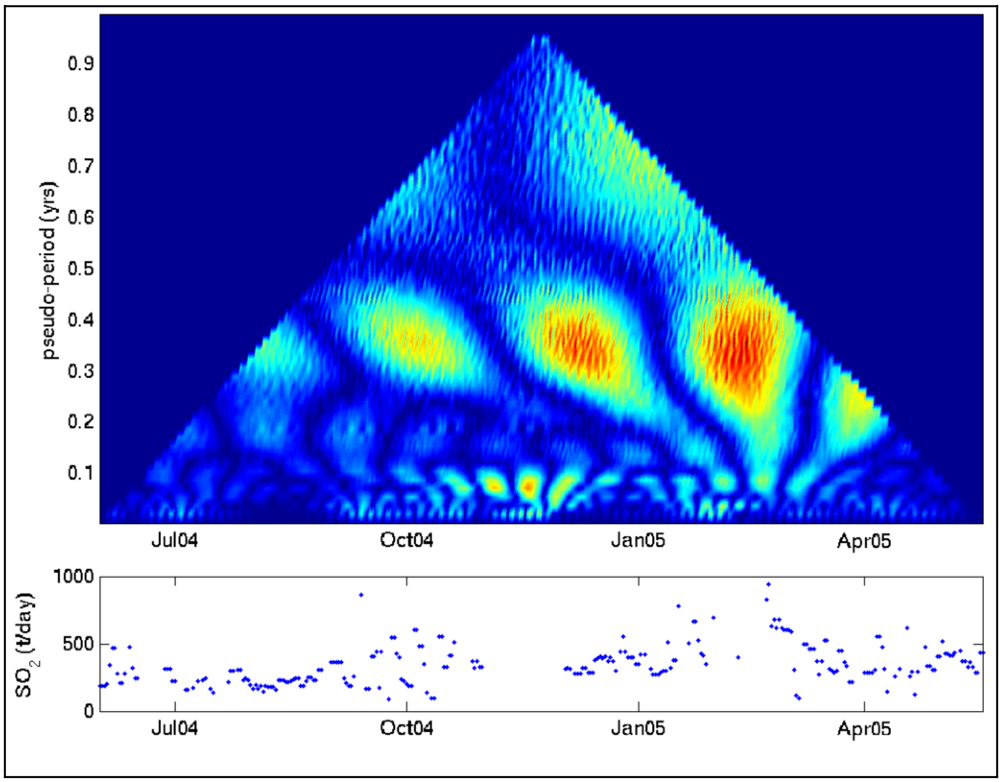

Figure 6 Wavelet plot of the SO_2 data from 2004 – 2005 showing the ~ 5 month cycle occurring during the second pause

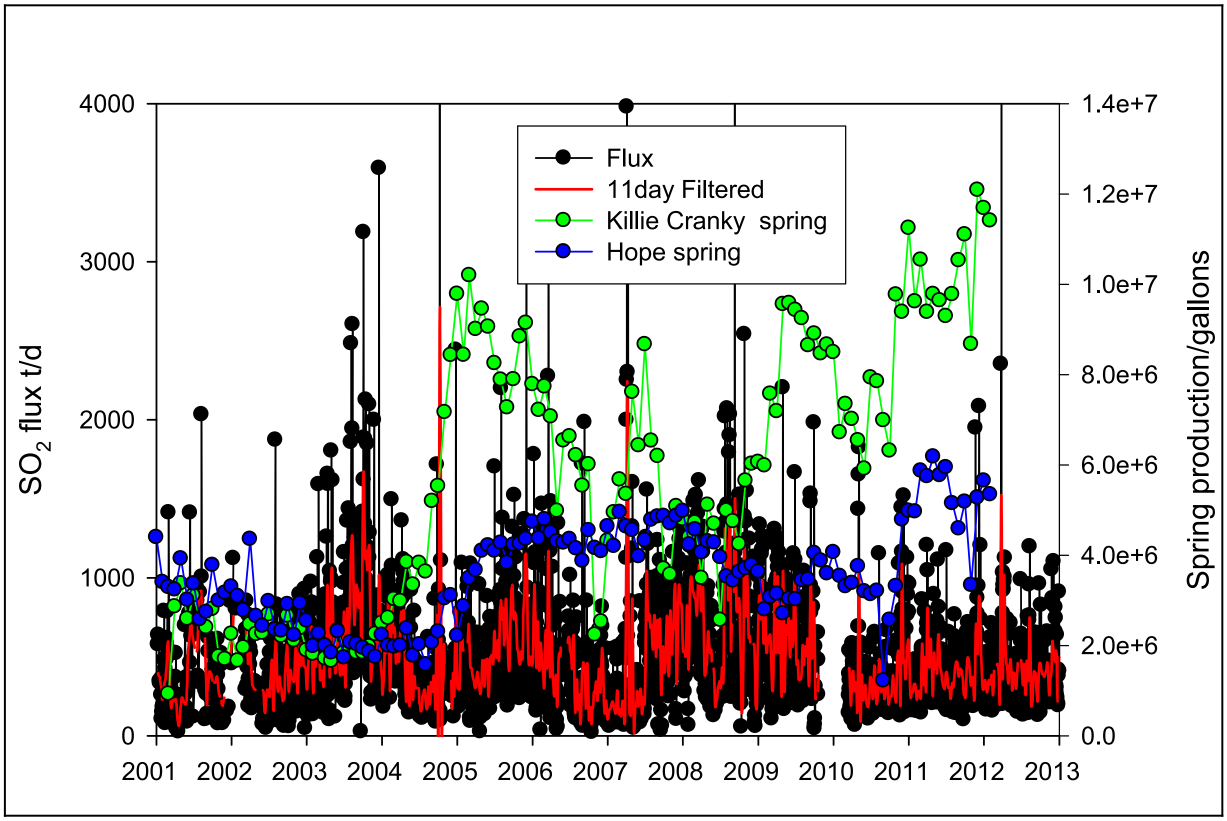

Figure 7 Comparisons of UV network flux data with production data from two center hills springs from 2001 till present

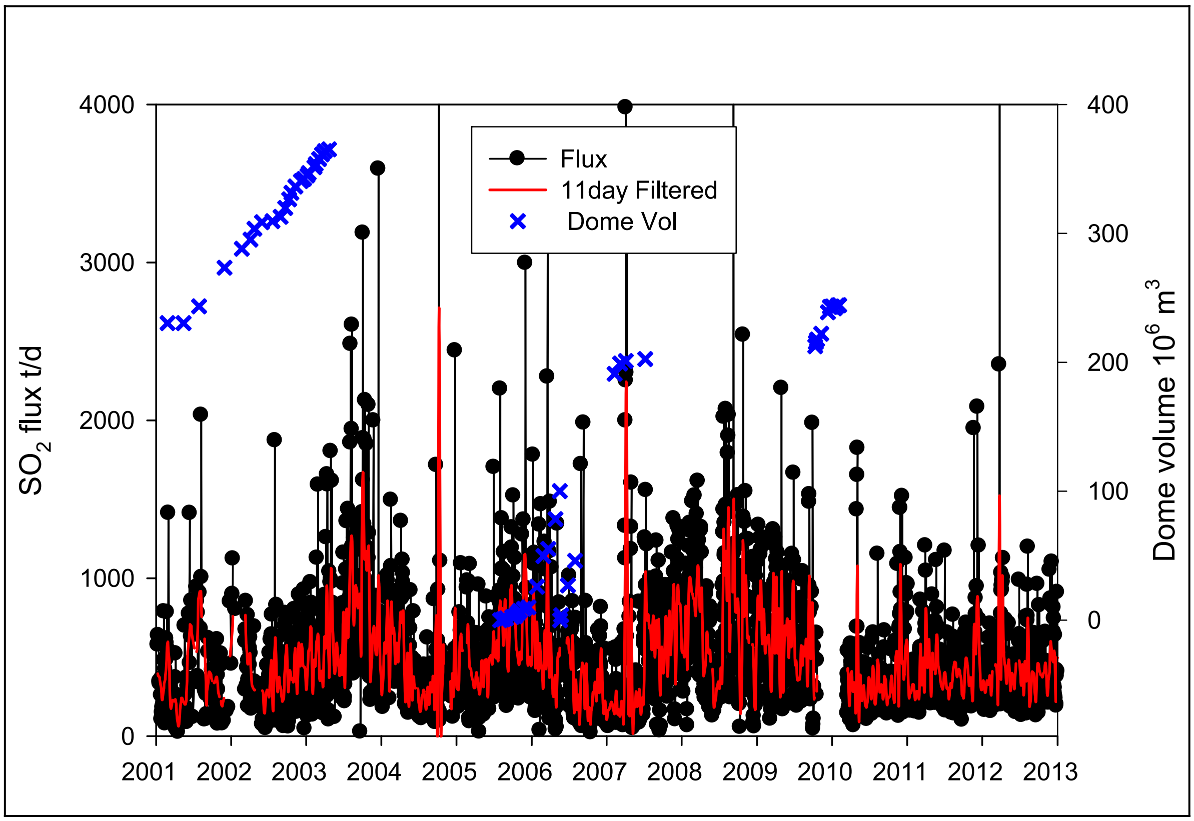

Figure 8 A comparison of dome volume and SO_2 flux from 2001 till present.

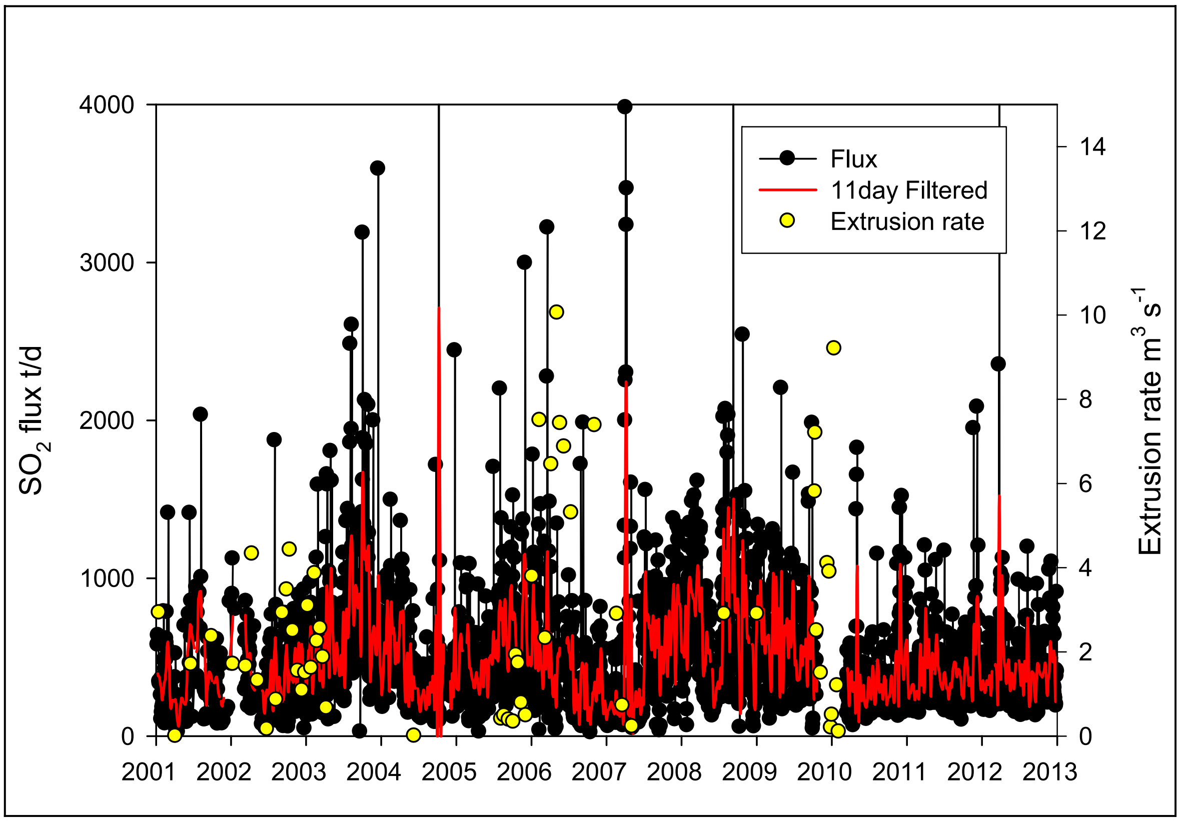

Figure 9 Andesite extrusion rate compared to daily SO_2 flux rates from 2001 till present