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Cyclical patterns in volcanic degassing revealed by SO_2 flux timeseries analysis: An application to Soufrière Hills Volcano, Montserrat ☆

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ABSTRACT

Cyclical patterns of behaviour in timeseries of seismic and geodetic data at volcanoes are frequently observed during lava dome-building eruptions, and are particularly well-documented from the current eruption of the Soufrière Hills Volcano (SHV), Montserrat. However, the discontinuous nature of many SO_2 measurements often preclude the identification and quantitative analysis of cyclical patterns in degassing data. Here, using a long SO_2 timeseries from SHV, with continuous measurements since 2002, we explore for the first time degassing behaviour at a resolution comparable to that possible for seismic and deformation datasets. Timeseries analysis of flux data spanning 2002–2011 reveals that SO_2 emissions at SHV exhibit complex cyclicity, with dominant cycles evident on both multi-year and multi-week (~50 day) timescales. These cycles persist through phases of both active extrusion and eruptive pause, and show close similarities to periodic components previously identified at SHV in timeseries of seismicity, ground deformation and lava extrusion.

The strength of expression or amplitude of degassing cycles, particularly on multi-week timescales, shows distinct temporal variation, and appears to correlate with the occurrence and nature of explosive activity occurring in 2002–2009. This suggests that the amplitude of surface gas flux cycles is modulated by physical conditions within the conduit. Direct quantitative comparison between seismicity, dome growth, and degassing for eruptive Phases 2 (2002–2003) and 3 (2005–2007) reveals that peaks in SO_2 flux appear to correspond broadly to enhanced lava extrusion and elevated seismicity within cycles of 30–50 days. However, time lags of 2, 4 and 7 days are observed between initial low-frequency seismic swarms and peaks in dome growth, SO_2 flux and rockfall event rate respectively. Multi-parameter correlations offer valuable insights into the controls on subsurface gas ascent, but further research is required to fully explore the contributions of permeability and overpressure, as well as other subsurface processes.

1. Introduction

Long-lived dome-forming eruptions are common features of andesitic volcanoes in subduction-zone settings (e.g., Newhall and Melson, 1983; Sparks, 1997). Activity is characterised by the extrusion of viscous, degassed, and often crystal-rich magma, which typically accumulates close to the vent and can build complex edifices ranging up to several cubic kilometres in volume. Dome-forming eruptions engender significant local hazards, because of the potential for catastrophic collapse, and the propensity for these systems to switch between effusive and explosive phases of activity (e.g., Matthews et al., 1997; Sparks and Aspinall, 2004; Voight et al., 1999).

The periodic behaviour of a number of parameters has been documented during many dome-forming eruptions, and probably reflects the fundamental eruptive mechanisms occurring at these volcanic systems during eruption. Cycles can either remain stable, or show systematic or non-systematic temporal changes (Denlinger and Hoblitt, 1999). Cycles in multiple physical observables, including lava efflux, seismic energy and event rate, ground deformation and degassing, have been observed at Mt St Helens (USA; Swanson and Holcomb, 1990), Santiaguito (Guatemala; Harris et al., 2003; Holland et al., 2011; Sahetapy-Engel et al., 2004) and Soufrière Hills Volcano (Montserrat; Edmonds et al., 2003a;

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Loughlin et al., 2010; Voight et al., 1999, 1998; Wadge et al., 2010; Watson et al., 2000; Young et al., 1998) among others (Table A; Supplementary information). Recent advances in geophysical monitoring have allowed systematic behaviour to be studied at increasingly fine time resolution. Nevertheless, much of the previous work in this field has focussed on single parameters (e.g., tilt deformation; Anderson et al., 2010; Voight et al., 1998), and less work has been done to analyse quantitatively the rich information contained within the multi-parameter geophysical and geochemical datasets that are increasingly common at well-monitored volcanoes (e.g., Aiuppa et al., 2010; Bonaccorso et al., 2011; Landi et al., 2011).

While spectral analysis is a well-developed tool for timeseries analysis in other parts of geosciences (e.g., climatology; Ghil et al., 2002; Mann and Lees, 1996) quantitative spectral analysis has only recently been applied in volcanology (Odbert and Wadge, 2009; Pearson et al., 2008). Here, we show how timeseries analysis techniques can be used to quantify the cyclical patterns of SO_2 flux at volcanic systems with long records of degassing data, and how quantitative analysis of long-term geophysical monitoring datasets can be used to reveal new insights into the behaviour of the volcanic system. Specifically, we use SO_2 flux timeseries data from Soufrière Hills Volcano (Fig. 1) to explore for the first time degassing trends at a resolution comparable to other geophysical parameters. Periodicities in SO_2 flux, and their temporal variability, are quantified and compared with characteristic timescales observed in other geophysical parameters in order to gain insights into the processes influencing shallow gas ascent.

1.1. Soufrière Hills Volcano, Montserrat

The current eruption at Soufrière Hills Volcano (SHV) began in 1995, and has been exceptionally well documented during both the early eruptive phases (e.g., Druitt and Kokelaar, 2002; Watts et al., 2002; Young et al., 1998), and as in more recent long-term overviews (Christopher et al., 2010; Luckett et al., 2007; Wadge et al., 2010). Activity is very broadly characterised by 2–3 yr ('multi-year') phases of active dome growth, separated by eruptive pauses (Fig. 1). Rapid transitions between effusive and explosive behaviour have been observed during some phases (e.g., Melnik and Sparks, 1999, 2005). During several extended periods of discrete explosions, for example, the explosive events are often correlated with cyclicity in other parameters, providing the potential for forecasting during these periods of quasi-systematic behaviour and evidence for links with conduit processes (Connor et al., 2003; Jaquet et al., 2006; Pyle, 1998; Watt et al., 2007). A series of Vulcanian explosions occurred at SHV in July 1997, each preceded by swarms of long-period seismicity and coincident with tilt cycle maxima (Voight et al., 1998). Similar behaviour has also been observed throughout later phases of the eruption, most notably in 2008–2010 (Odbert et al., in press). Studies integrating multiple parameters can therefore potentially provide significant insights into the mechanisms governing periodic behaviour.

Previous studies of the cyclicity observed in tiltmeter deformation and seismic events/amplitude timeseries at SHV have revealed both sub-daily (∼8 h) and multi-week (6–8 week or '50-day') timescales (Loughlin et al., 2010; Odbert and Wadge, 2009; Voight et al., 1998). Recent numerical models have shown these cycles to be mutually coupled, whereby variation in one cycle influences the amplitude and/or frequency of the other (Costa et al., 2013). Cyclical behaviour is often the result of multiple competing processes, with periodic stick-slip magma plug motion, in response to pressurisation in the shallow conduit, generally invoked to explain the sub-daily cycles (Costa et al., 2012, 2013; Denlinger and Hoblitt, 1999; Lensky et al., 2008; Thomas and Neuberg, 2012; Voight et al., 1999).

The numerical model of Costa et al. (2007a,b, 2013) represents the only attempt made thus far to model the longer multi-week cycles, and attributes cyclicity to feedbacks between magma ascent, seismicity and ground deformation associated with the periodic expansion and contraction of an elastic lower conduit dyke. The model produces a modulation of the magma flow into the shallow conduit over timescales of ∼50-days, driven by the periodic development and release of overpressure at dyke depths of 2–5 km. Higher amplitude tilt cycles, combined with overall deflation, and enhanced low-frequency (LF) seismicity occur during periods with elevated magma ascent rates early in each multi-week cycle (Costa et al., 2007a,b, 2013; Voight et al., 1999). Nevertheless, the implications of this model for degassing have only been addressed qualitatively. Initial attempts to link geophysical and degassing cycles were hindered by the challenges of regularly sampling SO_2 fluxes early in the eruption (e.g., Watson et al., 2000; Young et al., 2003). The installation of an automated network of UV-spectrometers in 2002 permitted collection of a

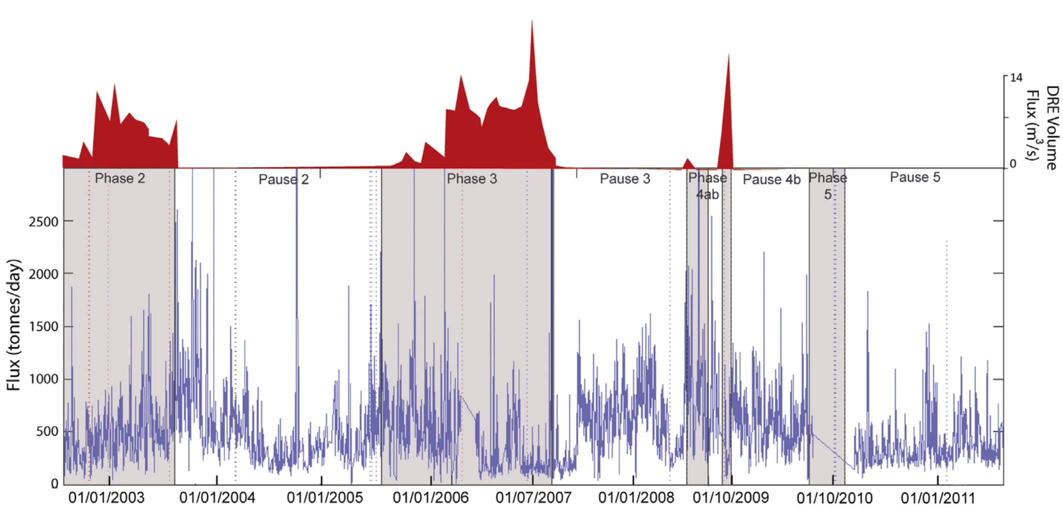

Fig. 1. Timeseries of daily mean SO_2 flux since the onset of continuous daily sampling (2002–2011) acquired by MVO using the instrumentation and methodology detailed in Edmonds et al. (2003b). Periods of active dome growth are annotated and highlighted (shaded regions) with the variable rates of magma efflux shown at the top in red in units of dense rock equivalent (DRE) volume (2002–2009; Wadge et al., 2010). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)