



Evidence for a new shallow magma intrusion at La Soufrière of Guadeloupe (Lesser Antilles) Insights from long-term geochemical monitoring of halogen-rich hydrothermal fluids



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ABSTRACT

More than three decades of geochemical monitoring of hot springs and fumaroles of La Soufrière of Guadeloupe allows the construction of a working model of the shallow hydrothermal system. This system is delimited by the nested caldera structures inherited from the repeated flank collapse events and the present dome built during the last magmatic eruption (1530 AD) and which has been highly fractured by the subsequent phreatic or phreatomagmatic eruptions. Because it is confined into the low volume, highly compartmented and partially sealed upper edifice structure, the hydrothermal system is highly reactive to perturbations in the volcanic activity (input of deep magmatic fluids), the edifice structure (sealing and fracturing) and meteorology (wet tropical regime). The current unrest, which began with a mild reactivation of fumarolic activity in 1990, increased markedly in 1992 with seismic swarms and an increase of degassing from the summit of the dome. In 1997 seismic activity increased further and was accompanied by a sudden high-flux HCl-rich gas from summit fumaroles. We focus on the interpretation of the time series of the chemistry and temperature of fumarolic gases and hot springs as well as the relative behaviours of halogens (F, Cl, Br and I). This extensive geochemical time series shows that the deep magmatic fluids have undergone large changes in composition due to condensation and chemical interaction with shallow groundwater (scrubbing). It is possible to trace back these processes and the potential contribution of a deep magmatic source using a limited set of geochemical time series: T, CO₂ and total S content in fumaroles, T and Cl⁻ in hot springs and the relative fractionations between F, Cl, Br and I in both fluids. Coupling 35 years of geochemical data with meteorological rainfall data and models of ion transport in the hydrothermal aquifers has allowed us to identify a series of magmatic gas pulses into the hydrothermal system since the 1976–1977 crisis. The contrasting behaviours of S- and Cl-bearing species in fumarolic gas and in thermal springs suggest that the current activity is the result of a new magma intrusion which was progressively emplaced at shallow depth since ~1992. Although it might still be evolving, the characteristics of this new intrusion indicate that it has already reached a magnitude similar to the intrusion that was emplaced during the 1976–1977 eruptive crisis. The assessment of potential hazards associated with evolution of the current unrest must consider the implications of recurrent intrusion and further pressurisation of the hydrothermal system on the likelihood of renewed phreatic explosive activity. Moreover, the role of hydrothermal pressurisation on the basal friction along low-strength layers within the upper part of the edifice must be evaluated with regards to partial flank collapse. At this stage enhanced monitoring, research, and data analysis are required to quantify the uncertainties related to future scenarios of renewed eruptive activity and magmatic evolution.

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1. Introduction

Long-term monitoring of geochemical and geophysical parameters of shallow hydrothermal systems has been undertaken at numerous active volcanic areas (Newhall and Dzurisin, 1988), such as Flegrean

Fields (Chiodini et al., 2003), Long Valley caldera (Sorey et al., 2003), Yellowstone (Lowenstern et al., 2006; Hurwitz et al., 2007), Mt Baker (Crider et al., 2011) and La Soufrière of Guadeloupe (Villemant et al., 2005). In these volcanic areas, unrest events have been interpreted as driven by magmatic processes at depth, involving the transfer of heat and fluids from magma intrusions to the shallow hydrothermal system. However numerous processes not directly related to magmatic activity may lead to similar changes in hydrothermal systems. These complex

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processes increase the difficulty of interpreting monitoring data (see e.g., Todesco, 2008, 2009; Moretti et al., 2013). The composition of magmatic and hydrothermal fluids collected in active volcanic areas is highly sensitive to the magma source composition and degassing processes at high temperature, but also to their lower temperature evolution and interactions with the surrounding hydrothermal systems during their shallow transfer paths (see e.g. Giggenbach, 1987, 1988; Symonds et al., 2001 among others). Monitoring the background composition, temperature and fluxes of magmatic and hydrothermal fluids over long periods of time thus constitutes a major tool for short-term hazard evaluation during unrest conditions.

The last major magmatic eruption at La Soufrière of Guadeloupe occurred in 1530 AD (Boudon et al., 2008; Komorowski, 2008) and possibly in 1635 (Hincks et al., 2014). Six historical phreatic eruptions have occurred since 1635 AD, namely in 1690, 1797–98, 1812, 1836–37, 1956, and 1976–77 (Komorowski et al., 2005). The July 1976–March 1977 eruption was particularly violent and complex (Feuillard et al., 1983; Komorowski et al., 2005). The lack of adequate monitoring and knowledge of the eruptive past contributed significantly to scientific uncertainty and the difficulty of reaching a consensual expert scientific judgement on the likely scenarios for the evolution of the crisis (Komorowski et al., 2005; Feuillard, 2011; Hincks et al., 2014; Beauducel, Soufrière 1976–77 web page). Hence, the study and management of this eruption were particularly difficult for scientists and national authorities. Since this eruption, La Soufrière of Guadeloupe has become one of the best monitored volcanoes in the world, with a network of pluridisciplinary methods that are implemented by the “Observatoire Volcanologique et Sismologique de La Soufrière de Guadeloupe” (OVSG-IPGP). Permanent networks monitor seismicity and ground deformations. Sampling and analysis of the physico-chemistry of thermal springs, fumaroles and acid ponds on a fortnightly base since 1979 have provided a continuous data record over ~35 years (see OVSG-IPGP, 1978–2012, 1999–2013). This large extended baseline dataset is a unique opportunity to analyse in details the long-term evolution of the magmatic–hydrothermal system of a seldomly erupting explosive andesitic volcano.

The 1976–1977 crisis has been interpreted either as a failed magmatic eruption (Feuillard et al., 1983), or as triggered by the pulsatory behaviour of the surficial hydrothermal system (Boudon et al., 1989; Zlotnicki et al., 1992). The geochemical surveys from 1979 to 2000 evidenced a series of major geochemical anomalies in thermal springs around the dome. These anomalies have recently been interpreted as the consequence of the intrusion of a small volume of andesitic magma at shallow depth which triggered the phreatic explosions in 1976–1977 and then, through a slow crystallisation–degassing process, episodically injected gas pulses into the shallow hydrothermal system (Villemant et al., 2005; Boichu et al., 2008, 2011). This model is supported by Cl isotope investigations (Li et al., 2012). More recently, on the basis of noble gas and C isotope studies, Ruzié et al. (2012, 2013) have proposed a similar model where the gas flux generated by a new fresh magma injection at depth is modulated by the shallow hydrothermal system and the sealing of the edifice.

Since 1976, the geochemical anomalies recorded in hot springs have progressively decreased with time and vanished for most springs between 1992 and 1995. The sustained fumarolic activity that developed on and around the dome during the 1976 crisis vanished initially very rapidly from the dome summit in 1977 and then decreased more progressively at the base of the dome to disappear almost completely in 1981. From 1992, though the geochemical anomalies in hot springs continued to decline, fumaroles at the summit of the dome were progressively reactivated, and a persistent high flux of HCl-rich H₂O vapour appeared in late 1997 (Komorowski et al., 2001; Bernard et al., 2006). Two small intermittent acid ponds were emplaced during that period at the summit of the dome (Komorowski et al., 2005). From 2006, as most springs reached a steady composition, a single spring, Galion, registered a new series of Cl anomalies culminating in 2009. Heat flux

that is mainly driven by the main summit fumaroles increased by a factor of ~3 from 2005 to 2010 (Beauducel Pers. Com. see also Allard et al., 2014). In parallel, since the end of the 1976–1977 crisis, the seismic activity rapidly decreased (<10 earthquakes/month from 1984 to 1985) to reach a minimum in 1990 (OVSG-IPGP Website, n.d). No other major anomalous geophysical signals were recorded between the end of 1977 and 1992. Since the end of 1992 the monitoring system has recorded a progressive increase in shallow and low energy seismicity (VT, LP), and a slow rise of temperature of thermal springs close to the dome (OVSG-IPGP Website, n.d). This situation of unrest at La Soufrière of Guadeloupe and its related phenomenology are not clearly understood at the present time. A magmatic origin cannot be excluded. How to identify the possible intrusion of a new magma batch as seems to have occurred during the 1976–1977 volcanic crisis?

Numerous studies have shown that geochemical monitoring provides valuable insights as to processes in the deep magmatic system that can be responsible for unrest recorded at the surface (Symonds et al., 2001; Chiodini et al., 2010; Crider et al., 2011; Melián et al., 2012; Moretti et al., 2013). Halogens are of particular interest because they display simple behaviours at high temperature during magma degassing at relatively shallow level and gas transfer to the surface (Symonds and Reed, 1993; Villemant et al., 2003, 2005; Balcone-Boissard et al., 2010). Halogens (F, Cl, Br and I) display simple behaviours during magma differentiation and degassing because they generally have low mineral/melt partition coefficients and high H₂O vapour–melt partition coefficients. Experimental data show that halogens are highly soluble in silicate melts in the absence of an exsolved H₂O vapour phase and that their volatile behaviour is mainly controlled by H₂O degassing (Webster et al., 1999; Aiuppa et al., 2008 and references therein). Cl, Br and I are extracted as halogen acids (HCl, HBr, HI) from the magma with similar vapour–melt partition coefficients, whereas F is not significantly extracted and remains concentrated in silicate melts (Villemant and Boudon, 1999; Balcone-Boissard et al., 2010). Halogen contents in magmatic gases are almost not modified by decompression, gas–wall rock interactions or cooling (down to temperatures ~120 °C) during ‘dry transfer path’, i.e. without interaction with a shallow hydrothermal system or atmospheric gases (Symonds and Reed, 1993). If gas interacts with hydrothermal or phreatic waters (‘wet transfer path’) halogen acids are completely dissolved (‘scrubbing effect’) and transported as conservative ions in low temperature aqueous systems (Symonds et al., 2001; Villemant et al., 2005). From these properties it is inferred that halogen abundance ratios (Cl/Br/I) of the degassing magmas are preserved in gases from high to intermediate temperatures (T > 120 °C) when they are transferred through a ‘dry path’ to the surface as observed, for example, in Mt Etna fumaroles (Aiuppa et al., 2005). These halogen ratios can also be preserved when halogen acids are completely dissolved in phreatic and hydrothermal systems. However, halogens may be highly fractionated during low temperature gas condensation (<120 °C), boiling of acid or ion-rich waters or precipitation of halides in highly concentrated brines (see e.g. Berndt and Seyfried, 1997 and references therein). Halogen speciation in the gas plume may also be highly modified by mixing with oxidising atmospheric gas and photocatalytic reactions (Bobrowski et al., 2003; Gerlach, 2004; Millard et al., 2006; Oppenheimer et al., 2006; Aiuppa et al., 2008; Villemant et al., 2008; von Glasow et al., 2008). Thus halogen systematics in volcanic fluids provide an efficient tool for identifying their origin and transfer histories, including condensation–evaporation and dissolution–precipitation processes, which is the goal of geochemical surveys of active volcanoes.

In this paper we present and interpret the geochemical time-series data (temperature and chemical compositions) that was measured during about 35 years of sampling of hot springs, fumaroles and acid ponds between 1979 and the end of year 2012. It extends the 1979–2003 data series from hot springs only that was discussed by Villemant et al. (2005) and focuses more specifically on halogens (F, Cl, Br, I) and temperature records. The interpretation of gas monitoring data remains

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