Soliciting hydrothermal systems

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SOLICITING HYDROTHERMAL SYSTEMS: THE CASE OF LA SOUFRIÈRE OF GUADELOUPE (FWI) UNREST.

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Introduction

The Grande Découverte - Soufrière complex is made up of three stratovolcanoes, Grande Découverte, Carmichael and Soufrière which were built during the last 445 000 years. Soufrière is the most recent building and its eruptive history began about 9150 years ago. It is an active volcano, explosive type, which has experienced many magmatic and non-magmatic eruptions, the latter called "phreatic", in the past. The most recent major magmatic eruption dates from 1530 AD. The historical activity of La Soufrière since 1635 is characterized by non-magmatic eruptions, which were minor in 1690, 1812, and 1956, and major in 1797-1798, 1836-1837, and 1976-1977 [1]. The phreatic eruption of 1956 lasted ten days with two explosions. That of 1976-77 was particularly violent with 26 major explosions between July 1976 and March 1977. It was a phreatic or hydrothermal eruption, which can also be considered as a failed (aborted) magmatic eruption, in which the magma did not rise to the surface. The state-of-the-art knowledge on phreatic eruptions reveals that *i*) they are typically frequent and sudden, *ii*) precursory signals are frequently absent or few and equivocal, *iii*) they are characterized by a variable duration and intensity, and *iv*) the associated phenomena are varied and can be particularly dangerous up-close. The great majority of phreatic eruptions are not systematically followed by a magmatic eruption.

Methods and results

Since late 2017 we have improved the fumarole sampling involving "Giggenbach" type soda bottles [2]. The temporal evolution of the chemical composition of fumarolic emissions can be qualitatively interpreted by interpreting ratios or chemical species. The variation in the gas/water vapor ratio essentially measures the variation of the relative proportion of magmatic gas to the meteoric component (rainwater) in the hydrothermal system; this ratio may increase due to the arrival of magmatic gases and / or the condensation of steam. The C/S ratio can increase during the rise of deep magmatic gases or by loss of sulfur, especially H_2S (gas scrubbing) in the hydrothermal system, often associated with a decrease in temperature. An increase in the CO_2/CH_4 ratio is considered as a clear signal of the arrival of oxidized hot magmatic gases enriched in CO_2, whose arrival oxidizes and potentially warms the base of the hydrothermal system, limiting the conversion of CO_2 in CH_4. Finally, the CO/CO_2 ratio, for an oxidation state set within the system, is normally associated with the heating of the hydrothermal system. It is also recalled that in hydrothermal systems characterized by the coexistence of water vapour and liquid (pure water or brines), the heating and overpressure phenomena are associated, so that temperature and pressure increase together. On the dome of the volcano, the fumarole CSC is the most representative for the monitoring and study of the La Soufrière hydrothermal system. The Figure 1 shows the variation of these molar ratios at this fumarole CSC.

It should be noted that the ratio gas/steam, stable since 11/2017, rose considerably on 2nd June (up to 0.1), before falling on 21st June 2018 and vary between 0.03 and 0.06. The C/S ratio, after reaching a minimum (3) at the end of March, rises to a peak of 6 in September 2018, then goes back to 4 in February 2019 and after shows values between 4 and 6. The CO_2/CH_4 ratio shows a general upward trend, with values rising sharply at the end of April and beginning of May (200 000 to 250 000). This ratio reaches a peak of the same value as late April at the beginning of June and in September. Same as in early June 2018, this ratio has an average value of around 150,000 since October 2018, ranging between 120,000 (February and April 2019) and 170,000 (November 2018 and January 2019). In June the ratio had values around 100,000, in line with those of November 2017, but since July 2019 it decreased to around 80,000.

Overall, the behavior of these indicators is related to the increase of the deep magmatic gas component in the hydrothermal system, which seems to be recurrent when comparing the C/S and CO_2/CH_4 values recorded in September and early June 2018.

The progressive infiltration of magmatic deep gas was responsible for the rise in the CO/CO_2 ratio, which peaked at the end of April - beginning of May, typically in response to a process of deep heating of the hydrothermal system. As of June, this indicator has returned to a baseline value that has been identified since November 2017, which fluctuates between 0.000005 and 0.00001 with a minimum (0.000003) in September 2018. Since then, the CO/CO_2 ratio fluctuates around a value of 0.0000050.

Discussion and conclusions

The infiltration of deep magmatic gases caused an increase in temperature and pressure inside the hydrothermal system, at depths of 2-3 km, compatible with the hypocenters of the seismic swarms recorded between February and April 2018 [3]. The latest data show that the Soufrière volcanic system is governed by the cyclically dynamics of energy recharge and discharge due to the infiltration of deep magmatic gases into the hydrothermal system. This generates a recurring process of overheating and overpressuring of the boiling hydrothermal fluids whose pressure and temperature conditions approach those of the critical point of water. Also the accumulation and energy released has, for the moment, reached its peak with the strong seismic and fumarolic activity of March-April 2018. Given the clear infiltration of magmatic gases into the hydrothermal system, as well as the high temperatures and pressures inside the hydrothermal system, we estimate that the volcanic system is currently recharging energy.

Steam-dominated summit fumaroles result from the boiling of the hydrothermal deep aquifer, solicited by the arrival of magmatic gases [3-4]. They also show chemical variations related to anomalous (and deeper than usual [3]) magmatic gas inputs. This, in turn, provoked thermoelastic solicitation of the hydrothermal system, leading to hydrofracturing and/or hydroshearing.

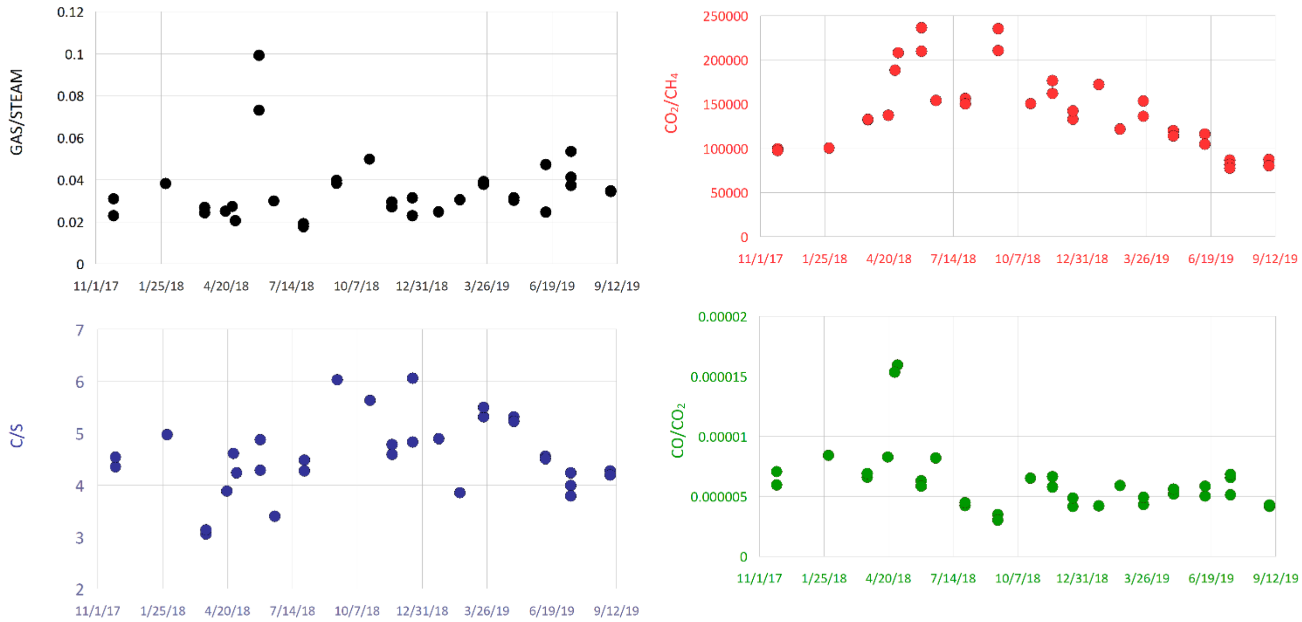

Figure 1: Chronograms of variations of molar ratios at the South Crater CSC fumarole. Peaks in the left panels mark the discharge of magmatic gas. Peaks in the right panels mark the heating and overpressurization of the hydrothermal system. Note the correspondences with the M 4.1 EQ on 27 April 2018

Depending on the thermochemical data treatment, important P-T variations can be calculated. Here we follow the approach by Cardellini et al. [5]), which is based on a set of thermometers and barometers derived by reaction equilibrium chemistry restricted to the system CO_2-CO-H_2, under the obvious hypothesis of two-phase vapor-liquid coexistence to fix the partial pressure of the steam. Although H_2O is the dominant component, its abundance may be biased by secondary phenomena (e.g., late steam condensation). In the literature many authors prefer then to assume PH_2O from steam tables at the temperature of interest. This latter is computed from the measured CO/CO_2 ratio coupled to a typical oxybarometer fixing oxygen fugacity, fO_2, with temperature (see [5-6] for details)

Despite much has to be said yet about the transient behavior of the overpressure source (« pulsatory degassing ») versus the structural modulation of the volcanic system, the recent 2018 unrest producing the M 4.1 earthquake on 27 April 2018 (Figures 1 and 2) was related to an « extra » supply of deep and hot magmatic gases which added up to the usual magmatic basal flux. This batch was discharged after the 27 April 2018 earthquake, as shown by the increase in CO_2/CH_4 (Figure 1). These gas batches may trigger phreatic eruptions, like the 1976-77, but represent a magmatic forcing related to magma dynamics at depth. *Is this magma a residual of the past (e.g., 1530) or is it a new emplacing magma?* The relatively few data that we have do not allow answering definitely to such a question. However, it can be clearly said that in 20 years the system evolved toward hotter conditions, which can lead to the drying of the hydrothermal system. This long-term process is however accompanied by short-term thermal and baric transients, such as the one embracing the M 4.1 earthquake occurred on 27 April 2018 and related to an increase of several degrees and bars in fluid temperature and pressure (Figure 2). The sudden overpressure of around 20 bar computed in this study can further increase under the undrained conditions occurring on the fault plane (off-volcanic axis) that slipped on 27 April 2018, due to pore pressure build-up which escalated up to rock failure.

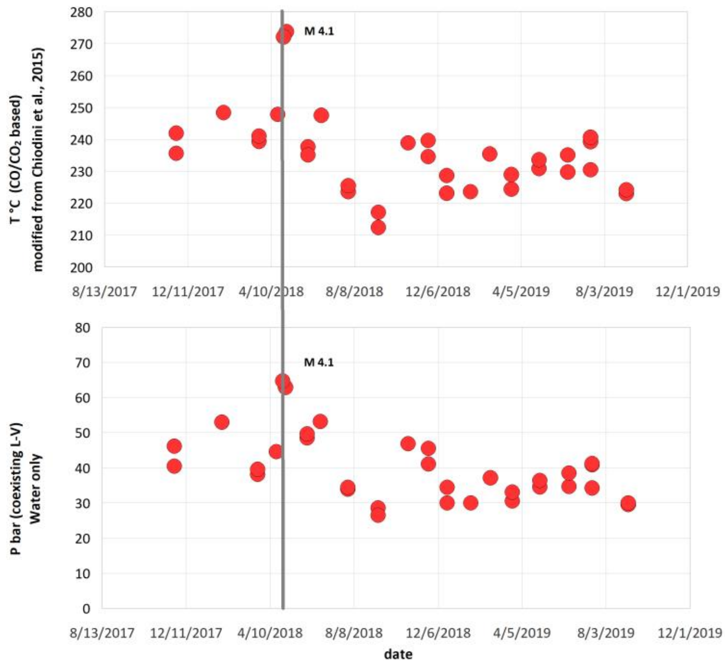

Figure 2*: P-T computed for the hydrothermal reservoir feeding the summit fumaroles (drained conditions). Under tha approximation adopted in this study an anomaly of around 20°C and 20 bar occurred in correspondence with the M 4.1 earthquake on 27 April 2018. This is in line with the CO/CO_2 peak observed the same day in fumarolic chemistry (Figure 2)*

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