Multiple magma degassing sources at an explosive volcano

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ABSTRACT

Persistent degassing of closed-conduit explosive volcanoes may be used to inspect and monitor magmatic processes. After interaction with shallow hydrothermal fluids, volcanic gases collected at surface can differ substantially from those exsolved from magma. We report here on an innovative approach to identify and separate the contribution of variable magmatic components from fumarolic gases, by processing the 30-year-long geochemical dataset from the Campi Flegrei caldera, Southern Italy. The geochemical record shows periodic variations, which are well correlated with geophysical signals. Such variations are interpreted as due to the time-varying interplay of two magma degassing sources, each differing in size, depth, composition, and cooling/crystallization histories. Similar multiple degassing sources are common at explosive volcanoes, with frequent ascent and intrusion of small magma batches. Our innovative method permits the identification of those magma batches, which contributes to the interpretation of unrest signals, forecasting and assessment of volcanic hazards.

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1. Introduction

Magmas contain variable amounts of volatile components, which can exsolve in a separate gas phase upon their decompression during ascent and/or crystallization. Both processes depend on bulk magma chemistry, temperature, and rheology (e.g., Parfitt and Wilson, 2008); therefore, volcanic gas compositions can, in principle, be inverted to quantify physical and chemical parameters of the degassing magma. Gas plumes at open conduit volcanoes are directly related to magma degassing within the volcanic system, allowing therefore a straightforward use of the gas composition to track evolution of the magmatic system (Aiuppa et al., 2010, 2007). On the contrary, gases released at closed conduit volcanoes, usually associated with explosive eruptions, have to rise through cold, permeable and fractured rocks that usually host hydrothermal fluids (Giggenbach, 1996, 1987). In such cases, volcanic gases that reach the surface result from chemical reactions, heat transfer and mixing between magmatic and hydrothermal components. Under such circumstances, retrieving information on the deep magmatic components can be extremely complex, and generates ambiguities when interpreting variations in the degassing patterns recorded at the surface (e.g., Chiodini et al., 2006).

We have developed a general method for exploring the relationships between magmatic and hydrothermal components and assessing their relative contributions to the gases discharged at closed-conduit explosive volcanoes. Our method combines long geochemical records with highly accurate oxygen isotopic data and multi-component gas–melt equilibrium modelling. The database is represented by the 30-year-long record of accurate chemical and isotopic data on fumarolic effluents (Chiodini et al., 2011, 2010a) of the Solfatara crater from the restless Campi Flegrei caldera (CFc) (Orsi et al., 1999, 1996). The CFc system has been deeply investigated and monitored for decades because of its very high volcanic risk (Orsi et al., 2009, 2004; Selva et al., 2012), providing a detailed reconstruction of the volcanic and deformation history over the last tens of thousands of years (Orsi et al., 2009, 1996), as well as petrologically- and geophysically-consistent pictures of both architecture and evolution of the magmatic feeding system (Arienzo et al., 2010; Di Renzo et al., 2011; Mangiacapra et al., 2008).

Application of the method shows that the recorded chemical variations reflect changes occurring in the magmatic gas component, and result from the interplay of two degassing sources that differ in depth, size, and crystallization time-scale. This conclusion provides a consistent and robust scenario that can be generalized to other closed-conduit volcanoes. According to this scenario, rise, emplacement at shallow depth, and cooling of a small magma batch is a short-term tuning effect over a long-term degassing trend imposed by a large, deep, and long-lived reservoir from which the small magma batch separated.

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2. Data analysis

Fumarolic gases (below with subscript "f") from the Solfatara crater at CFc are about 99% H_2O, CO_2 and H_2S, plus minor amounts of H_2, CO, CH_4. Previous investigation demonstrated that the fumarolic emissions at CFc are fed by a nearly monophasic and uncondensing gas plume that separates from the deepest (2–2.5 km) and hottest portion of the hydrothermal system, the latter interacting with ascending magmatic gases at conditions close to the H_2O critical point (Caliro et al., 2007). Such interaction is so profound that acid species in the magmatic gases, like HCl, HF and SO_2, are completely scrubbed (Symonds et al., 1991).

Gas species concentrations at Solfatara crater display oscillations that have been related to discrete pulses of deep magmatic gas mixing with hydrothermal fluids (Chiodini et al., 2010a; D'Auria et al., 2011; Gottsmann et al., 2006; Todesco and Berrino, 2005). $H_2O_{(f)}/CO_{2(f)}$ ratios display minima (Fig. 1a) reflecting periods of an increased contribution of a CO_2-rich magmatic gas (Caliro et al., 2007; Chiodini et al., 2010a; D'Auria et al., 2011).

The corresponding variation of $CH_{4(f)}/CO_{2(f)}$ ratios (Fig. 1b), which are unaffected by H_2O condensation, testifies that large amounts of oxidized magmatic fluids episodically enter, dilute and pressurize the hydrothermal system, inhibiting CH_4 formation (Chiodini et al., 2010a). Ingression of magmatic fluids in the hydrothermal system can also be tracked from the $H_2S_{(f)}/CO_{2(f)}$ ratio (Fig. 1c). Because $H_2S_{(f)}$ is generally fixed by equilibrium with hydrothermal pyrite, fluctuations of such a ratio depend on (1) variations in CO_2 partial pressure (P_{CO_2}) imposed, still at equilibrium with pyrite, by the proportion of magmatic and hydrothermal components in the fumarolic gases (Chiodini et al., 2010b), and (2) perturbations of the equilibrium with hydrothermal pyrite. When CO_2-rich, hot and oxidized magmatic fluids enter the hydrothermal system, $CH_{4(f)}/CO_{2(f)}$ and $H_2S_{(f)}/CO_{2(f)}$ ratios are expected to reach minimum values (Fig. 1). All these minima are usually not synchronous, reflecting different mobility and interaction mechanisms of the variable gas species in the hydrothermal system (Chiodini et al., 2010a; Todesco and Berrino, 2005).

Despite temporal gaps prior to 1998, oxygen isotopes ($\delta^{18}O_{H_2O(f)}$) of fumarolic steam condensates have been almost stable except the period around 1985 when a short-term dipping was observed and around June 2000, when they peaked at around −0.5‰ (BG and BN), before declining to −2‰ in 2007 (Fig. 1d), and do not show appreciable similarity with the other geochemical indicators, despite a peak in $\delta^{18}O_{H_2O(f)}$ value being observed in year 2000 in correspondence with minimum $CO_{2(f)}$ contents. It is worth noting that Pisciarelli datapoints plot at $\delta^{18}O_{H_2O(f)}$ values lower than Bocca Grande and Bocca Nuova ones, compatibly with the different outlet temperature of fumaroles (Fig. 1d).

A time correspondence exists between maxima and minima in $H_2O_{(f)}/CO_{2(f)}$, $CH_{4(f)}/CO_{2(f)}$, $H_2S_{(f)}/CO_{2(f)}$ gas ratios and ground deformation residuals (Fig. 1a–e). Moreover, after year 2000 both ground deformation residual and geochemical indicators show nearly monotonic trends. Seismicity occurs (i) during the 1982–84 uplift, with activity lasting till 1985, (ii) in correspondence with the maxima in ground deformation residuals (1989, 1994, 2000) and (iii) after 2005, with a long-lasting activity which follows the aforementioned nearly monotonic behaviour (Fig. 1f). These elements suggest a causal relationship between deep degassing and geophysical observables (Chiodini et al., 2011, 2010a; D'Auria et al., 2011, 2012; Gottsmann et al., 2006; Todesco and Berrino, 2005; Todesco et al., 2010).

Since year 2000 the geochemical trends at fumaroles show remarkable differences from the preceding two decades (Chiodini et al., 2010a,b). While the period 1982–2000 was characterized by oscillations, post-2000 trends correspond to a substantially continuous increase in CO_2 relative to H_2O and S contents. From 2010, $H_2O_{(f)}/CO_{2(f)}$ ratio appears to have attained a stable value around 3.3 (Fig. 1a).
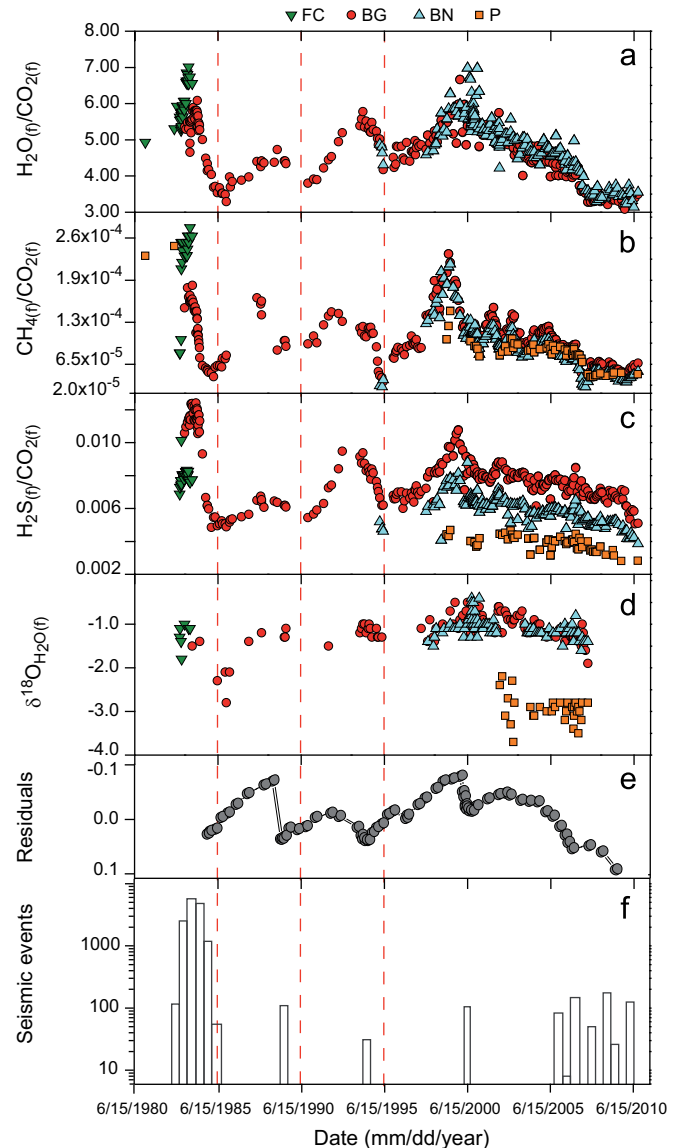

Fig. 1. Chronograms of relevant geochemical and geophysical observables. Molar $H_2O_{(f)}/CO_{2(f)}$ (panel a), $CH_{4(f)}/CO_{2(f)}$ (panel b), $H_2S_{(f)}/CO_{2(f)}$ (panel c) ratios and $\delta^{18}O_{H_2O,f}$ values (panel d) have been determined on Solfatara fumarolic discharges (Caliro et al., 2007; Chiodini et al., 2011, 2010a) (FC: Fumarola Centrale; BG: Bocca Grande; BN: Bocca Nuova; P: Pisciarelli). Panels (e) and (f) show chronograms of ground elevation residuals (computed after addition of the secular subsidence and subtraction of a first-order exponential decay in time; Chiodini et al., 2010a), and seismicity (D'Auria et al., 2011), respectively. Note that ground elevation residuals are shown on a reversed axis to remark the strong correlation with $CH_{4(f)}/CO_{2(f)}$, the minima of which are anticipated by seismicity.

3. Methods and calculation

Based on the guidelines of Caliro et al. (2007), $\delta^{18}O_{H_2O(f)}$ data (Fig. 1d) are used in the frame of a refined inversion that yields the magmatic gas fraction mixing with the hydrothermal fluid, and the concentration of magmatic H_2O and CO_2. These will be used to track the patterns of magma degassing and constrain the degree of magma differentiation, by using thermodynamic tools for gas–melt equilibria.

3.1. Isotopic inversion

^{18}O fractionation between H_2O and CO_2 heavily affects isotopic gas composition, also in relatively low temperature discharges,