The role of syn-eruptive vesiculation on explosive basaltic activity at Mt. Etna, Italy

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Abstract

We investigated the dynamics of explosive activity at Mt. Etna between 31 August and 14 December 2006 by combining vesicle studies in the erupted products with measurements of the gas composition at the active, summit crater. The analysed scoria clasts present large, connected vesicles with complex shapes and smaller, isolated, spherical vesicles, the content of which increases in scoriae from the most explosive events. Gas geochemistry reports CO_2/SO_2 and SO_2/HCl ratios supporting a deep-derived gas phase for fire-fountain activity. By integrating results from scoria vesiculation and gas analysis we find that the highest energy episodes of Mt. Etna activity in 2006 were driven by a previously accumulated CO_2-rich gas phase but we highlight the lesser role of syn-eruptive vesicle nucleation driven by water exsolution during ascent. We conclude that syn-eruptive vesiculation is a common process in Etnean magmas that may promote a deeper conduit magma fragmentation and increase ash formation.

Keywords: Etna; fire-fountains; vesicle textures; volcanic degassing

1. Introduction

At basaltic volcanoes the style of eruptive activity may range from quiescent degassing to quiet lava effusions, mild Strombolian explosions up to violent fire-fountaining. The primary control on the eruptive style is volatile exsolution and transport within the volcanic conduit. Despite great improvement has been made in interpreting geophysical and geochemical signals produced by permanent monitoring networks located on persistently active volcanoes, as, for example, Mt. Etna and Stromboli (see website of the Istituto Nazionale di Geofisica e Vulcanologia, sezione di Catania (INGV-CT) www.ct.ingv.it), how gas is transported in basaltic magmas and, mostly, how this affects and/or determines changes in the eruptive style of basaltic volcanoes is not yet fully understood. In this paper we address this question by investigating the relationship between magma vesiculation, degassing and style of eruptive activity at the Southeast crater (SEC) of Mt. Etna, one of the most active and well studied volcanoes in the world, during the August-December 2006 eruption. Etna has been characterized since 2000 by eruptions that exhibited a diversity of explosive behaviour (Behncke and Neri, 2003; Andronico et al., 2005; Taddeucci et al., 2004), including episodes of vigorous fire-fountaining generally accompanied by emission of ash columns a few km high above the summit craters (Alparone et al., 2003; Andronico et al., 2008). The duration and intensity of this activity in the last few years have had a severe impact on the overall economy of Eastern Sicily. Therefore understanding magma dynamics at this volcano not only allows a better assessment and forecasting of the volcanic hazard in this area but also provides insights into mechanisms of eruption inception, progression and shift between eruptive styles at persistently active basaltic volcanoes.

Because the nature of the gas phase (gas bubbles) is recorded in eruptive products as vesicles, in this paper we first characterize vesicle textures in scoria clasts from selected explosive episodes of the 2006 Etna activity by combining 2-D and 3-D textural analysis. Next we report measurements of the gas composition at SEC during some of these episodes and provide constraints to the source depth of the powering gas phase. By integrating the results on scoria vesiculation with information on the dynamics of degassing obtained by analysing the gas composition, we present a model that explains magma rise and fragmentation during the most explosive activity at Etna in 2006 via the superposition of two distinct degassing mechanisms. Finally, we discuss the implications of this model on ash formation during the eruption.

2. Summary of the August-December 2006 Mt. Etna eruptive activity and sample collection

Following the 10-day long eruption in mid July 2006 (Neri et al., 2006), and after a pause of more than a month, eruptive activity resumed at Etna on 31 August 2006 and lasted until 14 December. The new eruption involved both lava effusion, with the opening of several, new effusive vents in the summit crater area and on the upper ESE flank of the volcano, and the development of a complex lava flow field, as well as explosive activity of variable intensity. This latter mainly focussed at SEC and generated 20 paroxysmal episodes, each prevalently characterized by mild to moderate Strombolian explosions that exhibited, since late October, increasing intensity up to quasi-sustained fire-fountaining. These explosions were often accompanied by ash emissions that determined the closure of the Catania airport for several days in a row starting from the 24 November episode (Fig. 1). For details on the eruption please refer to the daily reports on INGV-CT website.

The strict correlation between seismic signals and real-time monitoring of the ongoing volcanic activity via the video camera surveillance system of INGV-CT allowed us to exactly determine the start and duration of each paroxysmal episode, as well as to observe any transition in eruptive style. Collection of fresh scoria clasts during the eruption was difficult owing to the danger associated with sampling in an active volcanic area during explosive activity. We succeeded in collecting lapilli-size scoriae from three of the explosive episodes. These ranged in intensity from low to moderate energy Strombolian explosions (episodes of 20 and 23 October 2006, and samples 201006a and 231006, respectively, Table 1) to quasi-sustained fire-fountain activity with generation of a vigorous ash column 5 km high a.s.l. (episode of 24 November 2006, Fig. 1, and sample 241106, Table 1).

3. Methods

3.1 Textural analysis of erupted products

Textural characterization of scoria clasts was performed in the laboratories of INGV-CT via conventional 2-D imaging on backscattered scanning electron (BSE) images acquired with a LEO-1430 SEM at a range of magnifications (25X-2000X). Vesicularity and vesicle connectivity (vol % all and connected vesicles), and number density of isolated vesicles (number of isolated vesicles per unit area) were computed on binary (thresholded) versions of the BSE images, following Polacci et al. (2006a). Groundmass (microlites, < 30 μm) and bulk (microphenocrysts, < 30-100 μm, + phenocrysts, > 100 μm) crystal content were also measured on BSE images with the same procedure. The analytical uncertainty on vesicularity and crystallinity was ~ 5% and ~ 10%, respectively. Connected and isolated vesicles in scoria products from the January-June 2000 SEC Mt. Etna eruption were measured on BSE images of samples used in the work of Polacci et al. (2006a).

Selected scoriae from the 20 October 2006 activity were also processed by synchrotron X-ray computed microtomography (μCT). This procedure allowed us to visualize the internal structure of these clasts in 3-D and to successfully reconstruct scoria textures, such as small, isolated vesicles, that cannot be unambiguously recognized on 2-D thin sections. The experiments were run at the SYRMEP beamlime of the Elettra Synchrotron radiation facility of Basovizza (Trieste, Italy), where experimental conditions were a ring energy of 2.4 GeV, beam energy of 33 keV, CCD field of view of 18.0x12.0 mm^2, and a pixel size of 9 μm. Tomographic scans were reconstructed into 3-D digital volumes that were used to provide 3-D views of vesicle textures and to process individual vesicle volumes and vesicle number densities (Table 1). The analytical uncertainty using this technique was estimated to be < 5%. Volumes of isolated vesicles were used to define the size range of isolated vesicles measured on 2-D thin section images. Details of the experimental setup and of the tomographic procedure can be found in Polacci et al.(2006b).

3.2 FTIR measurements of gas composition

We collected gas absorption spectra using open-path Fourier transform infrared spectroscopy (OP-FTIR) with a Bruker OPAG-22 spectrometer working at 0.5 cm^{-1} resolution, with a ZnSe beamsplitter and LN_2-cooled MCT detector sensitive to radiation between 500 and 6000 cm^{-1} (Burton et al., 2003). The field of view of the instrument was 30 mrad.

We performed passive remote sensing measurements of the composition of volcanic gases released during explosive activity at SEC on 23 October and 16 November 2006 from SW of SEC, approximately 2 and 1.1 km respectively from the eruptive source. The low-intensity Strombolian activity observed on 23 October was similar in nature to the periods of low to moderate explosive activity at Etna observed frequently during the August-December 2006 eruption. Conversely, measurements on 16 November represent the most explosive end-member of activity during this eruption, and are used to compare with the similarly explosive events of 24 November, when the scoria samples analysed in this work were collected.

Gas path amounts (molecules.cm^{-2}) were determined using a nonlinear, least-squares-fitting program based on the Rodgers optimal estimation algorithm (Rodgers, 1976), and a forward model utilising spectral line data from the HITRAN 96 database (Rothman et al., 1998). We analysed several volcanic gas species, H_2O, CO_2, SO_2, HCl, HF and CO. The uncertainty was less than 5% for SO_2, HCl and HF, thanks to their negligible atmospheric background; whereas for CO_2 and H_2O it was higher, about 5-6%. Molar ratios were determined by linear regression between volcanic gases. Volcanic CO_2 and H_2O amounts were distinguished from atmospheric components in the scatter plots through the *y*-intercept of regression lines between their amount versus SO_2 amount (Fig.3a and b). The higher value of the *y*-intercept for the 23 October 2006 spectra is in agreement with a longer instrument-source distance.

4. Results

Pyroclasts from the August-December 2006 Mt. Etna explosive activity are vesicular to highly vesicular (70-81 vol% vesicles, Table 1), porphyritic rocks (16-27 vol% phenocrysts, vesicle-free), with groundmass crystal content ranging 10-20 %. Scoriae from Strombolian to quasi-sustained fire-fountain activity exhibit a high degree of connected vesicles (> 97 %) in all the investigated samples (Table 1). When viewed in 3-D, these vesicles consists of a population of large (from hundreds of microns to > 1 cm), coalesced individuals with slightly deformed to irregular, complex shapes (Fig. 2). Small (< 0.16-0.02 mm in size), spherical to sub-spherical, isolated vesicles are however ubiquitously distributed in the areas separating large vesicles (~1-3 %, Table 1, and Fig. 2). We note that the number density of small, isolated vesicles is higher in scoriae from fountain-fed, explosive activity ($3.4x10^2$ or $1.8x10^3$ per cm^2 of bulk or melt volume, respectively) than in products from mild Strombolian activity ($1.7x10^2$ or $4.2x10^2$ per cm^2 of bulk or melt volume, respectively). Vesicularity and connectivity measured in tomographic volumes of scoria clasts from 20 October are in agreement with values obtained by processing 2-D BSE images of the same samples (Table 1).

The molar ratios (CO_2/SO_2, SO_2/HCl and SO_2/HF, Fig. 3) of volcanic gas species are strongly contrasted between the low intensity explosions of 23 October and the paroxysmal event of 16 November 2006. The molar gas composition measured during the 23 October Strombolian event was 93.5% H_2O, 4.5% CO_2, 1.3% SO_2, 0.37% HCl, 0.30% HF and 0.004% CO. Molar ratios were CO_2/SO_2 = 3.6, SO_2/HCl = 3.4 and SO_2/HF = 4.1 (Fig. 3a, b). The higher energy event on 16 November instead produced a gas phase richer in CO_2: 89.33% H_2O, 9.37% CO_2, 1.08% SO_2, 0.166% HCl, 0.051% HF and 0.007% CO, yielding higher mean CO_2/SO_2 (8.7), SO_2/HCl (6.5), and SO_2/HF (21) molar ratios (Fig 3a, b).

5. Discussion

Our textural observations show that the scoriae investigated in this study contain a population of large, highly interconnected vesicles together with small, spherical, isolated vesicles, whose number density increases with increasing eruption intensity. At persistently active basaltic volcanoes, the former type of vesicles may result from gas segregation along preferential percolation pathways (as observed on Stromboli (Burton et al., 2007), while the latter is a clear marker of syn-eruptive vesicle nucleation (Polacci et al., 2006). Gas segregation may develop readily in basaltic magmas, where the low viscosity (Giordano et al., 2008) and relatively low to moderate magma ascent rates favour gas/magma separation in magma chambers, with consequent gas accumulation (Jaupart and Vergniolle, 1988, 1989). This process was proposed by Allard et al. (2005) to explain the CO_2-rich gas phase powering a fire-fountain on Mt. Etna in 2000, as opposed to an alternative process described by Parfitt and Wilson (1995) and Parfitt(2004) in which rapid magma decompression induces explosive syn-eruptive degassing, which would produce a less CO_2-rich gas phase. Our measurements of the gas composition at SEC in 2006 demonstrate that during intense explosive activity (i.e. 16 November 2006) the gas phase has a higher CO_2/SO_2 ratio (8.7) (Fig. 3a), higher than that observed during Strombolian activity ($CO_2/SO_2 = 3.6$); similar observations also hold for SO_2/HCl (Fig. 3b). This finding is in agreement with the model of Jaupart and Vergniolle (1988, 1989) and observations of Allard et al. (2005).

By integrating results on scoria vesiculation with information on the source depth of the explosive gas phase we provide a general model of magma rise and fragmentation at SEC in 2006 which is based on the superposition of two different degassing mechanisms. We infer that separation, accumulation and coalescence of deep-sourced, CO_2-rich gas vesicles in a rising, collapsed foam layer was the primary degassing mechanism driving the high energy explosive events like those on 16 and 24 November 2006. We also suggest that, upon foam collapse and rapid ascent along the conduit, syn-eruptive vesiculation occurred in the thin liquid film of magma representing the remnant of the foam structure, to which we ascribe the enhanced nucleation of small, isolated vesicles observed in the scoriae of the quasi-sustained fire-fountain activity of 24 November 2006.

The most likely candidate for rapid exsolution during magma ascent is H_2O, as this volatile species will still be partially dissolved within the CO_2-saturated magma foam layer stored 1.5km beneath the summit craters. At such depths, assuming a lithostatic pressure gradient, the concentration of dissolved H_2O would be ~1 wt%, compared with an original H_2O content of ~3.2 wt% (Spilliaert et al., 2006). Syn-eruptive degassing was therefore a minor contribution to the eruptive gas phase which was dominated by previously accumulated gas. However, syn-eruptive degassing may contribute to the fragmentation process, triggering a deeper fragmentation in the conduit and increasing the generation of ash as observed during the episode of 24 November 2006. This mechanism of ash formation differs from the collapses of crater walls invoked by Andronico and Cristaldi (2006) to describe ash emissions accompanying the end of an explosive episode at SEC, and agrees with the juvenile-rich (and lithic-poor) character of the 24 November ash (Taddeucci et al., 2007) indicating its derivation from primary magmatic fragmentation.

Conclusions

The textures of vesicles described in this paper have been observed in products from previous fire-fountain activity at SEC (Polacci et al., 2006), suggesting that they are common in scoriae erupted from explosive activity at Mt. Etna. In particular, small, spherical vesicles have been described in scoria clasts from the 4-5 September 2007 fire-fountain (Andronico et al., 2008) and quantified in products from fire-fountain episodes of the January-June 2000 eruption, where they have been also found to increase in abundance with increasing eruption explosivity (compare vesicle number density in samples from Strombolian vs sustained fountaining activity in 2000, Table 1). These observations, together with the results of this study, indicate that syn-eruptive vesiculation is a common process in erupting Etnean magmas. Such process should be included in models aimed at investigating the degassing dynamics at Mt. Etna in order to understand and eventually numerically model the eruptive processes at this volcano.

We suggest that the combined degassing mechanism proposed in this study to explain the most explosive episodes occurred at Etna between August and December 2006 can be thought of as a general, working model of fire-fountain activity occurring at SEC. This crater has been the most active of the Etna summit craters in the past 30 years. Hence, if further validated by new, combined studies on gas composition and vesicle textures in erupted products, this model has the potential of improving volcanic risk mitigation during explosive activity at Mt. Etna as well as other persistently active basaltic volcanoes characterized by similar eruptive behaviour.

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Figure captions

Fig. 1 Ash plume ~ 2 km above the Southeast Crater on Mt. Etna during the explosive activity of 24 November 2006 (photo by G. Norini).

Fig. 2 Backscattered electron images of textures in scoria clasts from (a) the 23 October and (b) 24 November 2006 explosive activity; in (c) and (d), respectively, tomographic slice and 3-D volume view of scoria clast from the 20 October 2006 explosive activity reconstructed with X-ray computed microtomography. In all images voids are vesicles, dark grey and white laths are plagioclase and mafic crystals, groundmass is lighter grey. Scale bar 1 mm for images in (a) and (b), x-axis length 3 mm in (c) and (d).

Fig.3 Scatter plot of gas amounts measured during low (23 October 2006) and high (16 November 2006) energy explosive activity at Mt. Etna in 2006: (a) CO_2 versus SO_2, (b) SO_2 versus HCl. See text for further explanation.