

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

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12

13 **Abstract**

14 We investigated the dynamics of explosive activity at Mt. Etna between 31 August and 14
15 December 2006 by combining vesicle studies in the erupted products with measurements of the gas
16 composition at the active, summit crater. The analysed scoria clasts present large, connected
17 vesicles with complex shapes and smaller, isolated, spherical vesicles, the content of which
18 increases in scoriae from the most explosive events. Gas geochemistry reports CO₂/SO₂ and
19 SO₂/HCl ratios supporting a deep-derived gas phase for fire-fountain activity. By integrating results
20 from scoria vesiculation and gas analysis we find that the highest energy episodes of Mt. Etna
21 activity in 2006 were driven by a previously accumulated CO₂-rich gas phase but we highlight the
22 lesser role of syn-eruptive vesicle nucleation driven by water exsolution during ascent. We conclude
23 that syn-eruptive vesiculation is a common process in Etnean magmas that may promote a deeper
24 conduit magma fragmentation and increase ash formation.

25

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

27

28 **1. Introduction**

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

49 Because the nature of the gas phase (gas bubbles) is recorded in eruptive products as vesicles, in
50 this paper we first characterize vesicle textures in scoria clasts from selected explosive episodes of
51 the 2006 Etna activity by combining 2-D and 3-D textural analysis. Next we report measurements
52 of the gas composition at SEC during some of these episodes and provide constraints to the source

53 depth of the powering gas phase. By integrating the results on scoria vesiculation with information
54 on the dynamics of degassing obtained by analysing the gas composition, we present a model that
55 explains magma rise and fragmentation during the most explosive activity at Etna in 2006 via the
56 superposition of two distinct degassing mechanisms. Finally, we discuss the implications of this
57 model on ash formation during the eruption.

58

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

60 Following the 10-day long eruption in mid July 2006 (Neri et al., 2006), and after a pause of more
61 than a month, eruptive activity resumed at Etna on 31 August 2006 and lasted until 14 December.

62 The new eruption involved both lava effusion, with the opening of several, new effusive vents in the
63 summit crater area and on the upper ESE flank of the volcano, and the development of a complex
64 lava flow field, as well as explosive activity of variable intensity. This latter mainly focussed at
65 SEC and generated 20 paroxysmal episodes, each prevalently characterized by mild to moderate
66 Strombolian explosions that exhibited, since late October, increasing intensity up to quasi-sustained
67 fire-fountaining. These explosions were often accompanied by ash emissions that determined the
68 closure of the Catania airport for several days in a row starting from the 24 November episode (Fig.
69 1). For details on the eruption please refer to the daily reports on INGV-CT website.

70 The strict correlation between seismic signals and real-time monitoring of the ongoing volcanic
71 activity via the video camera surveillance system of INGV-CT allowed us to exactly determine the
72 start and duration of each paroxysmal episode, as well as to observe any transition in eruptive style.

73 Collection of fresh scoria clasts during the eruption was difficult owing to the danger associated
74 with sampling in an active volcanic area during explosive activity. We succeeded in collecting
75 lapilli-size scoriae from three of the explosive episodes. These ranged in intensity from low to
76 moderate energy Strombolian explosions (episodes of 20 and 23 October 2006, and samples
77 201006a and 231006, respectively, Table 1) to quasi-sustained fire-fountain activity with generation

78 of a vigorous ash column 5 km high a.s.l. (episode of 24 November 2006, Fig. 1, and sample
79 241106, Table 1).

80

81 **3. Methods**

82 **3.1 Textural analysis of erupted products**

83 Textural characterization of scoria clasts was performed in the laboratories of INGV-CT via
84 conventional 2-D imaging on backscattered scanning electron (BSE) images acquired with a LEO-
85 1430 SEM at a range of magnifications (25X-2000X). Vesicularity and vesicle connectivity (vol %
86 all and connected vesicles), and number density of isolated vesicles (number of isolated vesicles per
87 unit area) were computed on binary (thresholded) versions of the BSE images, following Polacci et
88 al. (2006a). Groundmass (microlites, < 30 μm) and bulk (microphenocrysts, < 30-100 μm , +
89 phenocrysts, > 100 μm) crystal content were also measured on BSE images with the same
90 procedure. The analytical uncertainty on vesicularity and crystallinity was ~ 5% and ~ 10%,
91 respectively. Connected and isolated vesicles in scoria products from the January-June 2000 SEC
92 Mt. Etna eruption were measured on BSE images of samples used in the work of Polacci et al.
93 (2006a).

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

104 vesicles measured on 2-D thin section images. Details of the experimental setup and of the
105 tomographic procedure can be found in Polacci et al.(2006b).

106

107 **3.2 FTIR measurements of gas composition**

108 We collected gas absorption spectra using open-path Fourier transform infrared spectroscopy (OP-
109 FTIR) with a Bruker OPAG-22 spectrometer working at 0.5 cm^{-1} resolution, with a ZnSe
110 beamsplitter and LN₂-cooled MCT detector sensitive to radiation between 500 and 6000 cm^{-1}
111 (Burton et al., 2003). The field of view of the instrument was 30 mrad.

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

120 Gas path amounts ($\text{molecules}\cdot\text{cm}^{-2}$) were determined using a nonlinear, least-squares-fitting
121 program based on the Rodgers optimal estimation algorithm (Rodgers, 1976), and a forward model
122 utilising spectral line data from the HITRAN 96 database (Rothman et al., 1998). We analysed
123 several volcanic gas species, H₂O, CO₂, SO₂, HCl, HF and CO. The uncertainty was less than 5%
124 for SO₂, HCl and HF, thanks to their negligible atmospheric background; whereas for CO₂ and H₂O
125 it was higher, about 5-6%. Molar ratios were determined by linear regression between volcanic
126 gases. Volcanic CO₂ and H₂O amounts were distinguished from atmospheric components in the
127 scatter plots through the y-intercept of regression lines between their amount versus SO₂ amount
128 (Fig.3a and b). The higher value of the y-intercept for the 23 October 2006 spectra is in agreement
129 with a longer instrument-source distance.

130

131 **4. Results**

132 Pyroclasts from the August-December 2006 Mt. Etna explosive activity are vesicular to highly
133 vesicular (70-81 vol% vesicles, Table 1), porphyritic rocks (16-27 vol% phenocrysts, vesicle-free),
134 with groundmass crystal content ranging 10-20 %. Scoriae from Strombolian to quasi-sustained
135 fire-fountain activity exhibit a high degree of connected vesicles (> 97 %) in all the investigated
136 samples (Table 1). When viewed in 3-D, these vesicles consists of a population of large (from
137 hundreds of microns to > 1 cm), coalesced individuals with slightly deformed to irregular, complex
138 shapes (Fig. 2). Small (< 0.16-0.02 mm in size), spherical to sub-spherical, isolated vesicles are
139 however ubiquitously distributed in the areas separating large vesicles (~1-3 %, Table 1, and Fig.
140 2). We note that the number density of small, isolated vesicles is higher in scoriae from fountain-
141 fed, explosive activity (3.4×10^2 or 1.8×10^3 per cm^2 of bulk or melt volume, respectively) than in
142 products from mild Strombolian activity (1.7×10^2 or 4.2×10^2 per cm^2 of bulk or melt volume,
143 respectively). Vesicularity and connectivity measured in tomographic volumes of scoria clasts from
144 20 October are in agreement with values obtained by processing 2-D BSE images of the same
145 samples (Table 1).

146 The molar ratios (CO_2/SO_2 , SO_2/HCl and SO_2/HF , Fig. 3) of volcanic gas species are strongly
147 contrasted between the low intensity explosions of 23 October and the paroxysmal event of 16
148 November 2006. The molar gas composition measured during the 23 October Strombolian event
149 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
150 $\text{CO}_2/\text{SO}_2 = 3.6$, $\text{SO}_2/\text{HCl} = 3.4$ and $\text{SO}_2/\text{HF} = 4.1$ (Fig. 3a, b). The higher energy event on 16
151 November instead produced a gas phase richer in CO_2 : 89.33% H_2O , 9.37% CO_2 , 1.08% SO_2 ,
152 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
153 SO_2/HF (21) molar ratios (Fig 3a, b).

154

155 **5. Discussion**

156 Our textural observations show that the scoriae investigated in this study contain a population of
157 large, highly interconnected vesicles together with small, spherical, isolated vesicles, whose number
158 density increases with increasing eruption intensity. At persistently active basaltic volcanoes, the
159 former type of vesicles may result from gas segregation along preferential percolation pathways (as
160 observed on Stromboli (Burton et al., 2007), while the latter is a clear marker of syn-eruptive
161 vesicle nucleation (Polacci et al., 2006). Gas segregation may develop readily in basaltic magmas,
162 where the low viscosity (Giordano et al., 2008) and relatively low to moderate magma ascent rates
163 favour gas/magma separation in magma chambers, with consequent gas accumulation (Jaupart and
164 Vergnolle, 1988, 1989). This process was proposed by Allard et al. (2005) to explain the CO₂-rich
165 gas phase powering a fire-fountain on Mt. Etna in 2000, as opposed to an alternative process
166 described by Parfitt and Wilson (1995) and Parfitt(2004) in which rapid magma decompression
167 induces explosive syn-eruptive degassing, which would produce a less CO₂-rich gas phase. Our
168 measurements of the gas composition at SEC in 2006 demonstrate that during intense explosive
169 activity (i.e. 16 November 2006) the gas phase has a higher CO₂/SO₂ ratio (8.7) (Fig. 3a), higher
170 than that observed during Strombolian activity (CO₂/SO₂ = 3.6); similar observations also hold for
171 SO₂/HCl (Fig. 3b). This finding is in agreement with the model of Jaupart and Vergnolle (1988,
172 1989) and observations of Allard et al. (2005).

173 By integrating results on scoria vesiculation with information on the source depth of the explosive
174 gas phase we provide a general model of magma rise and fragmentation at SEC in 2006 which is
175 based on the superposition of two different degassing mechanisms. We infer that separation,
176 accumulation and coalescence of deep-sourced, CO₂-rich gas vesicles in a rising, collapsed foam
177 layer was the primary degassing mechanism driving the high energy explosive events like those on
178 16 and 24 November 2006. We also suggest that, upon foam collapse and rapid ascent along the
179 conduit, syn-eruptive vesiculation occurred in the thin liquid film of magma representing the
180 remnant of the foam structure, to which we ascribe the enhanced nucleation of small, isolated
181 vesicles observed in the scoriae of the quasi-sustained fire-fountain activity of 24 November 2006.

182 The most likely candidate for rapid exsolution during magma ascent is H₂O, as this volatile species
183 will still be partially dissolved within the CO₂-saturated magma foam layer stored 1.5km beneath
184 the summit craters. At such depths, assuming a lithostatic pressure gradient, the concentration of
185 dissolved H₂O would be ~1 wt%, compared with an original H₂O content of ~3.2 wt% (Spilliaert et
186 al., 2006). Syn-eruptive degassing was therefore a minor contribution to the eruptive gas phase
187 which was dominated by previously accumulated gas. However, syn-eruptive degassing may
188 contribute to the fragmentation process, triggering a deeper fragmentation in the conduit and
189 increasing the generation of ash as observed during the episode of 24 November 2006. This
190 mechanism of ash formation differs from the collapses of crater walls invoked by Andronico and
191 Cristaldi (2006) to describe ash emissions accompanying the end of an explosive episode at SEC,
192 and agrees with the juvenile-rich (and lithic-poor) character of the 24 November ash (Taddeucci et
193 al., 2007) indicating its derivation from primary magmatic fragmentation.

194

195 **Conclusions**

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

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

214

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218

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276 Figure captions

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

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

285 Fig.3 Scatter plot of gas amounts measured during low (23 October 2006) and high (16 November
286 2006) energy explosive activity at Mt. Etna in 2006: (a) CO₂ versus SO₂, (b) SO₂ versus HCl. See
287 text for further explanation.

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