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Magma vesiculation and infrasonic activity at Stromboli open conduit volcano

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ABSTRACT

Explosive activity at Stromboli is explained in terms of dynamics of large gas bubbles that ascend in the magma conduit and burst at the free surface generating acoustic pressure that propagates as infrasonic signals in the atmosphere. The rate and the amplitude of the infrasonic activity is directly linked to the rate and the overpressure of the bursting gas bubbles and thus reflects the rate at which magma column degasses under non-equilibrium pressure conditions.

We investigate the link between explosive degassing and magma vesiculation by comparing the rate of infrasonic activity with the bubble size distributions (BSDs) of scoria clasts collected during several days of explosive activity at Stromboli. BSDs of scoria show a characteristic power law distribution, which reflect a gas bubble concentration mainly controlled by a combined process of bubble nucleation and coalescence.

The cumulative distribution of the infrasonic pressure follows two power laws, indicating a clear separation between the frequent, but weak, bursting of small gas bubbles (puffing) and the more energetic explosions of large gas slugs. The exponents of power laws derived for puffing and explosive infrasonic activity show strongly correlated (0.96) changes with time indicating that when the puffing rate is high, the number of energetic explosions is also elevated. This correlation suggests that both puffing and explosive activity are driven by the same magma degassing dynamics. In addition, changes of both infrasonic power law exponents are very well correlated (0.92 with puffing and 0.87 with explosions) with variations of the BSD exponents of the scoria clasts, providing evidence of the strong interplay between scoria vesiculation and magma explosivity. Our analysis indicates that variable magma vesiculation regimes recorded in the scoria correlate with the event number and energy of the explosive activity. We propose that monitoring infrasound on active volcanoes may be an alternative way to look at the vesiculation process in open conduit systems.

1. Introduction

Volcanic eruptions involve the exsolution, growth and expansion of a gas phase during magma ascent towards the Earth's surface, resulting in large variations of the magma's rheological properties and changes in its dynamical regime when fragmentation occurs (Jaupart and Tait, 1990). Problems linked to the vesiculation and fragmentation of magma have long challenged geologists: vesiculation and degassing are the primary trigger of volcanic eruptions and amongst the most important factors controlling the rheology of magmas (Sparks, 1978; Gardner et al., 1996; Manga et al., 1998; Papale, 1999; Giordano and Dingwell, 2003). When magma ascends toward the surface, pressure in the column decreases, volatile solubility decreases and upon supersaturation, bubble nucleation begins.

Bubbles in fragmented, erupted magmas are usually regarded as a mixture of gases that nucleates and grows by decompression and diffusion in magma chambers, and/or during their ascent in the conduit (Sparks and Brazier, 1992; Mangan et al., 1993; Blower et al., 2002). The dynamics of vesiculation cannot be directly observed in the magmatic column, so the process of bubble nucleation and growth must be inferred from secondary sources such as theoretical studies (Proussevitch and Sahagian, 1998), laboratory investigations (Jaupart and Vergniolle, 1989; Mader et al., 1994; Blower et al., 2001; Namiki et al., 2003) and textural analysis of volcanic rocks (Cashman et al., 1994; Klug and Cashman, 1996; Mangan and Cashman, 1996). Vesiculation is frequently studied using bubble size distributions (BSD) and the integrated cumulative frequency–bubble size distribution of volcanic rocks (see, for example, Mangan et al., 1993; Gaonac'h et al., 1996a; Klug et al., 2002). According to their bubble size distribution, scoria and lava samples contain information on vesiculation during volcanic eruptions or magma degassing and allow us to infer magma chamber processes and conduit dynamics.

The present work combines textural analysis of scoria samples collected during the persistent explosive activity at Stromboli volcano (Aeolian Islands, Italy) with infrasonic activity recorded during the same period of the scoria collection.

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Explosive activity is evidence that part of the exsolved gas leaves the magma column in non-equilibrium pressure conditions. The bursting of gas bubbles is recorded as acoustic pressure which propagates in the atmosphere as an infrasonic wave. The infrasonic amplitude is a function of gas overpressure and bubble volume (Vergniolle and Brandeis, 1996; James et al., 2009).

At Stromboli, infrasound reveals that Strombolian explosions are associated with a persistent background activity of small (0.5–6 Pa) pressure transients occurring every ~2 s (Ripepe et al., 1996). This infrasonic activity represents the bursting of small gas bubbles in overpressurized conditions (puffing) and involves, at smaller scale but higher rate, the same magma breaking mechanisms (or shallow magma fragmentation) as the larger explosive events.

This persistent but weak gas bursting activity (puffing) accounts for ~50% of the total gas budget at Stromboli volcano (Harris and Ripepe, 2007; Ripepe et al., 2008) and can be considered as the active (non-equilibrium) counterpart of the passive magma degassing, which is silent in the infrasonic range (Harris and Ripepe, 2007). Considering that another ~10% of the gas budget is released by Strombolian explosive activity (Allard et al., 1994; Burton et al., 2007), more than ~60% of the total gas at Stromboli leaves the magma column in overpressurized conditions (Ripepe et al., 2008) and thus forms a major proportion of the degassing dynamics.

We compare the cumulative distribution of infrasonic pressures with the cumulative distribution of bubble sizes in scoria to investigate if variations in vesiculation measured in scoria clasts are related to variations in the degassing rate of the magma column both as puffing and as explosions. Our hypothesis is that these two processes reflect different aspects of the degassing process, where infrasound is the indirect but continuous measure of the magma column degassing in overpressurized conditions, while scoria clasts represent the discrete and discontinuous evidence of magma vesiculation.

We show that the correlation of the two datasets can provide important information about the vesiculation process in magmas.

2. BSD analysis on X-ray tomographic images

Quantitative data on the number, shape and size distributions of bubbles in volcanic scoria provide useful information about magma vesiculation processes as these parameters are directly related to the kinetics of bubble nucleation and growth, and/or to the influence of vesiculation rate on magma fragmentation (Cashman et al., 1994; Mangan and Cashman, 1996). BSD allows us to infer which processes (nucleation, diffusive growth, expansion or coalescence) dominate during magma fragmentation.

Quantitative analysis of bubble textures were obtained by processing 2D slices of tomographic images (~1.5×1.5 cm^2) of scoria products collected during normal Strombolian activity at Stromboli volcano in 2004, 2005 and 2006. These images were obtained from X-ray tomographic analysis performed at the SYRMEP beamline of Elettra Sincrotrone Trieste in Basovizza (Trieste, Italy).

X-ray computed microtomography (μCT) is a technique that can be used for imaging the inner 3D structure of volcanic rocks and measuring their physical properties (Fig. 1). This method is non-destructive, and provides large quantities of 2D and 3D micro-structural information of porous materials with micron-scale resolution (Proussevitch et al., 2007; Bai et al., 2008; Okumura et al., 2008; Polacci et al., 2009). Tomographic scans of each reconstructed scoria volume were analyzed with the software ImageJ (Abramoff et al., 2004), each 3D scan consisting of 200–400 2D slices, with a pixel size of 9 or 14 μm. For further information on the μCT technique and experimental conditions at the SYRMEP beamline refer to Polacci et al. (2006, 2009).

We processed images of 11 tomographic volumes related to scoria clasts collected during different periods of explosive activity at Stromboli. All samples were collected at the crater rim just after they were ejected and, therefore, they are very well defined both in time and space; for each scoria clast we know exactly the date, the crater from which they were ejected and the associated infrasonic activity.

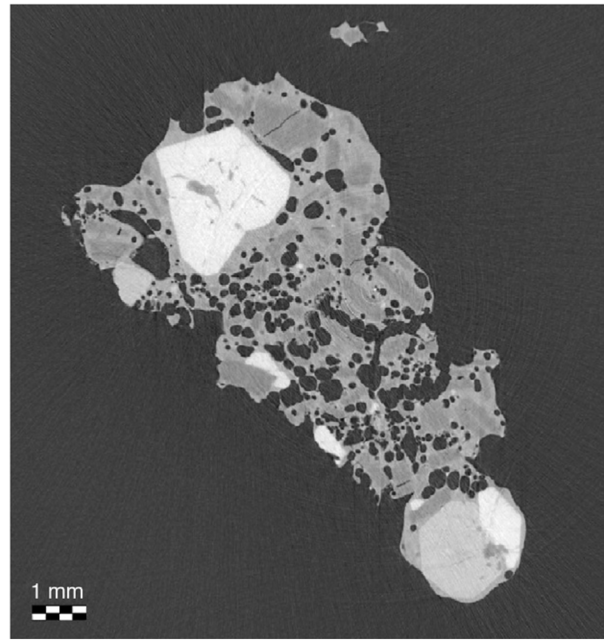

Fig. 1. One slice of 778 × 778 pixels, (1 pixel = 14 μm) of the scoria 20041221, obtained via synchrotron X-ray computed microtomography (μCT). Black holes are bubbles, light grey is glass and crystals are dark grey or white.

The tomographic images of scoria are characterized by small spherical or sub-spherical bubbles. All but one of the analyzed scoria samples show no textural and morphological features typical of post-fragmentation degassing (e.g., a vesicularity gradient) and do not contain very small crystals with irregular and uneven edges characteristic of secondary fragmentation (Taddeucci et al., 2004). Therefore, we consider that these scoria are representative of the state of the magma within the conduit before fragmentation. The scoria sample of April 14, 2006 shows a vesicularity gradient and was analyzed from top to bottom in three different tomographic runs (top, middle, and bottom), each run representing a different part of the sample.

Generally, 2D analysis of BSD is calculated on several images with different magnification of few (4–5) thin sections of the same scoria (e.g., Mangan and Cashman, 1996). According to the magnification level, each image contains different ranges of bubble sizes. The BSD calculated with this 2D procedure is strongly limited by the magnification used, by the possible presence of elongated (non-spherical) bubbles and, even if bubbles are spherical, by the disagreement between the diameter of the bubble on the slice plane and the true bubble diameter (stereology problem). Recently, all these problems have been solved by the use of 3D analysis on the tomographic 3D reconstruction of the scoria image (e.g., Polacci et al., 2009). However, this tomographic procedure is very time-demanding (4–5 days for a single scoria) and it is still not of common use. A comparison between 3D tomographic volumes and 2D processing of the same sample revealed that vesicularity and connectivity values are in quite good agreement to each other (Polacci et al., 2009). We thus preferred to apply the 2D technique to estimate BSD values, which can be better compared to previous vesicularity analyses. In addition, here we are interested in changes of magma vesicularity with time rather than a thorough description of the BSD of scoria samples at Stromboli, which can be found in Polacci et al. (2009).