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A new approach to investigate an eruptive paroxysmal sequence using camera and strainmeter networks: Lessons from the 3–5 December 2015 activity at Etna volcano

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ABSTRACT

Explosive sequences are quite common at basaltic and andesitic volcanoes worldwide. Studies aimed at short-term forecasting are usually based on seismic and ground deformation measurements, which can be used to constrain the source region and quantify the magma volume involved in the eruptive process. However, during single episodes of explosive sequences, integration of camera remote sensing and geophysical data are scant in literature, and the total volume of pyroclastic products is not determined. In this study, we calculate eruption parameters for four powerful lava fountains occurring at the main and oldest Mt. Etna summit crater, Voragine, between 3 and 5 December 2015. These episodes produced impressive eruptive columns and plume clouds, causing lapilli and ash fallout to more than 100 km away. We analyse these paroxysmal events by integrating the images recorded by a network of monitoring cameras and the signals from three high-precision borehole strainmeters. From the camera images we calculated the total erupted volume of fluids (gas plus pyroclastics), inferring amounts from 1.9×10^9 m^3 (first event) to 0.86×10^9 m^3 (third event). Strain changes recorded during the first and most powerful event were used to constrain the depth of the source. The ratios of strain changes recorded at two stations during the four lava fountains were used to constrain the pyroclastic fraction for each eruptive event. The results revealed that the explosive sequence was characterized by a decreasing trend of erupted pyroclastics with time, going from 41% (first event) to 13% (fourth event) of the total erupted pyroclastic volume. Moreover, the volume ratio fluid/pyroclastic decreased markedly in the fourth and last event. To the best of our knowledge, this is the first time ever that erupted volumes of both fluid and pyroclastics have been estimated for an explosive sequence from a monitoring system using permanent cameras and high precision strainmeters. During future explosive paroxysmal sequences this new approach might help in monitoring their evolution also to understand when/if they are going to finish. Knowledge of the total gas and pyroclastic fractions erupted during each lava fountain episode would improve our understanding of their processes and eruptive behaviour.

1. Introduction

Eruptive sequences and pulsatory or cyclic volcanic activity are common at basaltic and andesitic volcanoes, and involve different eruptive styles, magma rheology and degassing rates (Iguchi et al., 2008; Nicholson et al., 2013; Montanaro et al., 2016). The eruptive sequences of several volcanoes have been described: Sakurajima, Suwanosejima and Semeru (Iguchi et al., 2008; Dominguez et al., 2016), Shinmoe-dake (Takeo et al., 2013), Montserrat (Barmin et al., 2002; Nicholson et al., 2013), Etna (Andronico and Corsaro, 2011; Bonaccorso and Calvari, 2013; Behncke et al., 2014), Eyjafjallajokull (Sigmarsson et al., 2011; Dominguez et al., 2016), Santiaguito (Barmin et al., 2002; Harris et al., 2003), Colima (Robin et al., 1991; Webb et al., 2014), and Asama (Yaqui and Koyaguchi, 2004).

The periodicity of the explosions has been related to magma composition, with mafic explosions having greater frequency than those fed by intermediate or silicic magmas. The discontinuous explosive style observed at several open-conduit volcanoes has ultimately been attributed to magma viscosity, reflecting changes in crystallinity, volatile content or composition occurring across distinct flow regimes and fragmentation dynamics (Dominguez et al., 2016). Conduit flow regimes could be distinguished if eruptive parameters such as total mass erupted, discharge rate or outgassing dynamics were available, but unfortunately these parameters are

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rare, even for the best monitored volcanoes. Short-term predictive models of eruptions are typically based on geophysical monitoring information (Iguchi et al., 2008; Iguchi, 2016), whereas long-term forecasts are derived from the history of the volcano (Montanaro et al., 2016; Ort et al., 2016). Integration of remote sensing and geophysical data during explosive eruption sequences aimed at quantifying erupted gas and pyroclastics are scant in the literature. Far more attention is normally given to the quantification of fine-grained ash volumes transported in the ash plume because of their impact on aviation (Aloisi et al., 2002; Marzano et al., 2013; Donnadieu et al., 2016). Thus, the variability of the gas-pyroclastic ratio during explosive sequences is poorly known, although it could prove a highly useful parameter to understand the evolution of the process and possibly also to forecast its future development.

Prior to 2011, there were four craters on Etna's summit: Voragine (VOR), also named Central Crater, NE-Crater (NEC), Bocca Nuova (BN), and SE-Crater (SEC) (Fig. 1). Over the last two decades, SEC produced more than 100 lava fountains before the two main explosive and effusive flank eruptions of 2001 and 2002–2003 (Alparone et al., 2003; Bonaccorso et al., 2011). Seven additional lava fountains in 2007–2008, preceded a flank eruption in 2008–2009. A further 44 powerful lava fountain episodes took place from January 2011 to December 2013 (for a review see Bonaccorso and Calvari, 2013; Behncke et al., 2014; Bonaccorso et al., 2014; De Beni et al., 2015) from a new vent named New SE Crater (NSEC; Fig. 1B). These events caused the rapid growth of the NSEC, which in just three years reached a similar size to the SEC that formed over 40 years since 1971 (De Beni et al., 2015).

The Hawaiian or lava fountain style of volcanic activity involves the relatively steady discharge of magma, which is disrupted below the surface into a mixture of released gas and pyroclastics (Head and Wilson, 1987). The pyroclasts in the resulting fountains have a range of grain sizes, coarse enough so that little of the pyroclastic material is entrained into a convecting cloud over the vent (Wilson and Head, 1981). Most of the material returns to the surface to form pyroclastic cones, rootless flows or lava ponds (Head and Wilson, 1987; Sparks et al., 1997). Lava fountains at Etna and Stromboli volcanoes are often different from their Hawaiian counterpart for their explosive power and for the formation of a several kilometre high, sustained eruptive column expanding well beyond the lava fountain portion and causing widespread ash fallout (e.g. Calvari et al., 2011; Bonaccorso et al., 2014). It is for this reason that they have been identified with the adjective "paroxysmal" (e.g., Bonaccorso et al., 2012, 2013a; Gambino et al., 2016), in order to highlight their greater violence when compared to the Hawaiian lava fountains.

The frequent paroxysmal activity of the NSEC has generated critical situations due to the formation of high eruptive columns leading to significant ash plume dispersal and fallout deposits (e.g. Calvari et al., 2011; Bonaccorso et al., 2011, 2014; Marzano et al., 2013; Andronico et al., 2015). Depending on wind speed and direction, several lava fountains have caused problems to the infrastructure of the city of Catania and to other villages around Etna, as well as severe hazard to aviation and the frequent disruption of the Catania international airport (Marzano et al., 2013). The NSEC paroxysmal (fountaining) episodes were more powerful than the previous events from SEC occurring in 2000 (e.g. Alparone et al., 2003; Andronico and Corsaro, 2011). They lasted a few hours each, and comprised both an explosive component with several hundred meter high lava fountains (located inside the gas-thrust region portion of the eruptive column) and an effusive component generating lava flows with maximum lengths of 4–6 km (Calvari et al., 2011; Ganci et al., 2012, 2013; Gouhier et al., 2012; Behncke et al., 2014; De Beni et al., 2015). The average total volume of magma emitted during each of the 2011–2013 NSEC paroxysmal episodes, including both pyroclastics and lava flows, was $\sim 2.5 \times 10^6$ m^3 (Bonaccorso and Calvari, 2013), as determined by the effused lava (Ganci et al., 2012) and the pyroclastic deposit (Behncke et al., 2014) mean volumes for each episode. This average value is about one order of magnitude greater than the average volume erupted during each of the SEC lava fountains in 2000 (Alparone et al., 2003). The strain changes recorded during the 2011–2013 lava fountains inferred a source located at sea level that is associated with the depressurization of a shallow storage feeding the lava fountains (Bonaccorso et al., 2013a, 2013b).

The VOR has been much less active than the NSEC in recent decades, with the last two main eruptive episodes being a subplinian explosion on 22 July 1998 (Aloisi et al., 2002; Bonaccorso, 2006) and a powerful lava fountain on 4 September 1999 (Calvari et al., 2002; Harris and Neri, 2002). After these two episodes, VOR was generally quiescent for several years. VOR suddenly produced four powerful lava fountain episodes between 3 and 5 December 2015 (Fig. 1). These were exceptional both for their eruptive power and rapid occurrence rate. Overall, the paroxysmal events of 3–5 December 2015 rank among the most violent to occur at Etna in the last two decades.

In this paper, we present an integration of continuous recordings of thermal cameras and high precision borehole strainmeters to infer the volumes of gas and pyroclastics released during four paroxysmal episodes at Etna volcano between 3 and 5 December 2015. The volumetric flow rate is usually obtained from plume heights based on theoretical or field-based empirical relations (e.g. Sparks et al., 1997; Mastin et al., 2009). In our study, the analysis from cameras is applied only to the lower part of the entire eruptive column, i.e. the lava fountain comprising only the 1–2 km high, innermost portion of the "gas-thrust region", which is below the convective regime portion and below the upper umbrella region expanding laterally (Fig. 1).

We investigated these four VOR eruptive episodes using the images recorded by two thermal monitoring cameras (EMOT and ENT, see Fig. 1 and Table 1) and three borehole strainmeters (DRUV, DEGI and DMSC, Fig. 1). Firstly, we estimated the total emitted fluid volume (gas plus pyroclastic) using the camera images and inferred the depth of the source through the strain changes. Then we used a novel approach that combined the information from strain changes inferring the pyroclastic volumes for each lava fountain with the fluid volumes used to estimate the percentage of the pyroclastics with respect to the total volume emitted during the sequence events. We discuss the possible connections and differences with the previous lava fountain episodes at NSEC, and present a possible way to recognise the end of future explosive sequences.

2. Methods. Camera and borehole strainmeter networks

2.1. Camera network

The sequence of eruptive events has been reconstructed using the time-lapse images recorded by the network of monitoring cameras, comprising thermal cameras. Details of the instruments used are listed in Table 1 and their positions are in Fig. 1.

The erupted volume can be inferred from the height of the lava fountain column, i.e. the lowest and sustained part of the eruptive column corresponding to the innermost portion of the gas-thrust region, as defined by Sparks et al. (1997) in their Fig. 1.18. We have calculated the erupted fluid volume (gas plus pyroclastics) during each lava fountain episode using the following equations (Wilson, 1980; Vergniolle and Ripepe, 2008):

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