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Dynamics and time evolution of a shallow plumbing system: The 1739 and 1888–90 eruptions, Vulcano Island, Italy

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ABSTRACT

In this work we analyze the morphology of latitic enclaves occurring in the rhyolitic lava flow of Pietre Cotte (Island of Vulcano, Italy). We show that enclave morphology is a feature inherited from the shallow plumbing system of the volcano during the invasion of the latitic magma into the rhyolitic magma. The complexity of enclave morphology is quantified by fractal analyses. Using the empirical relationship given by Perugini et al. (2005) relating the fractal dimension and viscosity ratio, the range of viscosity ratios that developed during the injection of the latitic magma into the rhyolitic one is estimated.

Thermodynamical and rheological modeling indicates that the most plausible scenario to explain the variability of observed viscosity ratios is represented by a plumbing system where a large volume of latitic magma intruded a smaller volume of rhyolitic magma. The comparison of volume proportions of magmas on the outcrop with those estimated by the modeling allows us to infer that most of the latitic magma remained in the plumbing system after the ending of the 1739 eruptive cycle.

The strong similarity of compositions from the Pietre Cotte lava flow and products erupted during the last volcanic activity of Vulcano (1888-1890) is interpreted as the reactivation of the latitic magma, that possibly evolved through fractional crystallization to produce trachy-rhyolitic compositions, during the 1888–1890 eruptive cycle. We suggest that the methodological approach presented here can represent a further tool for hazard mitigation in volcanic areas. In particular, it allows obtaining information about the dynamics of plumbing systems of active volcanoes and their time evolution.

1. Introduction

Magma mixing/mingling patterns are common features in volcanic rocks (e.g. Bacon, 1986; Calanchi et al., 1993; Perugini et al., 2003a, 2003b; Ventura, 2004), and the processes responsible for their formation have been a subject of intense research (e.g. Eichelberger, 1980; Snyder, 2000; Perugini et al., 2004). Such patterns include enclaves, banding, and vortex-like structures (e.g. Bacon, 1986; Perugini et al., 2003a, 2003b; Perugini and Poli, 2012). Although studies on the mineralogical and geochemical features of mixed rocks are abundant (e.g. Poli and Tommasini, 1991; Bateman, 1995; Perugini et al., 2003a, 2003b; Gioncada et al., 2005; Viccaro et al., 2006; De Campos et al., 2008; Perugini et al., 2010), less efforts have been made to quantify mixing patterns igneous bodies (Wada, 1995; Ventura, 1998; Smith, 2000; De Rosa et al., 2002; Perugini et al., 2002; Perugini et al., 2003a, 2003b). These studies were mainly focused on (i) the deformation of the interface between interacting magmas in laminar and turbulent flows, (ii) the effects of vesiculation on the deformation of enclaves, and (iii) the relationships between the morphology of the mingling/mixing structures and the degree of magma interaction. Studies on the fluid-dynamics of interacting liquids (e.g. Ottino, 1989; Liu et al., 1994; Voth et al., 2002; Morgavi et al., 2013a), as well as magma mixing experiments (e.g. Morgavi et al., 2013b; Perugini et al., 2013, 2012), and analyses of natural patterns (e.g. Ventura, 2004; Gonnermann and Manga, 2005; Albert et al., 2015), have shown that the different morphological structures can give useful information about mixing dynamics and eruptive styles (e.g. Perugini, 2002; Perugini et al., 2007; Albert et al., 2015).

Recently, the study of mixing patterns, complemented by high resolution geochemical data on both experimental magma mixing time series and natural outcrops, was used to infer eruption dynamics and deciphering the time-scales of volcanic eruptions (e.g. Perini et al., 2004; Martin et al., 2008; Perugini et al., 2010).

In this contribution we study the morphology of latitic enclaves dispersed in an obsidian lava flow of rhyolitic composition (Pietre Cotte lava flow, A.D. 1739) cropping out on the island of Vulcano (Aeolian Archipelago, Southern Italy). The complexity of enclave morphology is quantified by measuring the fractal dimension of enclave boundaries. Results are interpreted in the light of the physical processes responsible for the production of the variable enclave morphology. A model relating the viscosity ratio between the enclaves and the host magma is

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proposed to estimate the volumes of magmas that interacted in the plumbing system of Vulcano before the eruption of the Pietre Cotte lava flow. These estimates, along with the comparison between the geochemical composition of the Pietre Cotte enclaves and eruptive products from the 1888–1890 eruption, are used to infer the dynamics and time-evolution of the plumbing system of this active volcano from the period immediately before 1739 to 1888–1890 eruptions.

2. Outcrops features and fractal analysis of enclaves

The studied lava flow, known as "Pietre Cotte", was erupted from Vulcano "La Fossa" cone in 1739 (Keller, 1980; Frazzetta et al., 1983; De Astis et al., 1997) (Fig. 1). It is an obsidian lava with rhyolitic composition in which enclaves of latitic composition are dispersed (Fig. 2). Hereafter, latitic enclaves will be termed as "mafic" enclaves since their composition is less evolved compared to the host rhyolitic mass. The rhyolitic (hereafter, "felsic") rock is characterized by a banded aspect due to the occurrence of alternate glassy and pumiceous bands, whose elongation is parallel to the direction of the lava flow (Fig. 2). The host rock is phenocryst free and a spherulitic texture due to devitrification is commonly observed. Mafic enclaves have a glassy groundmass with phenocrysts (25-30% in volume) of clinopyroxene, plagioclase and minor amounts and opaque minerals. Felt-like textures mainly constituted by acicular crystals of feldspars are commonly found in the groundmass.

Mafic enclaves constitute 5–6% of the whole outcrop. In general, they have crenulated to angular margins and the interface between enclaves and the rhyolitic host is well defined (Fig. 2 and 3). The morphology of enclaves can be better seen in Fig. 3. Although enclaves are characterized by highly variable shapes, from highly convoluted to almost rounded, they share some common features: (i) the contact with the rhyolitic magma displays fingers of the mafic magma directed towards the host magma (Fig. 3) and (ii) in many cases enclaves display cuspate terminations (Fig. 3).

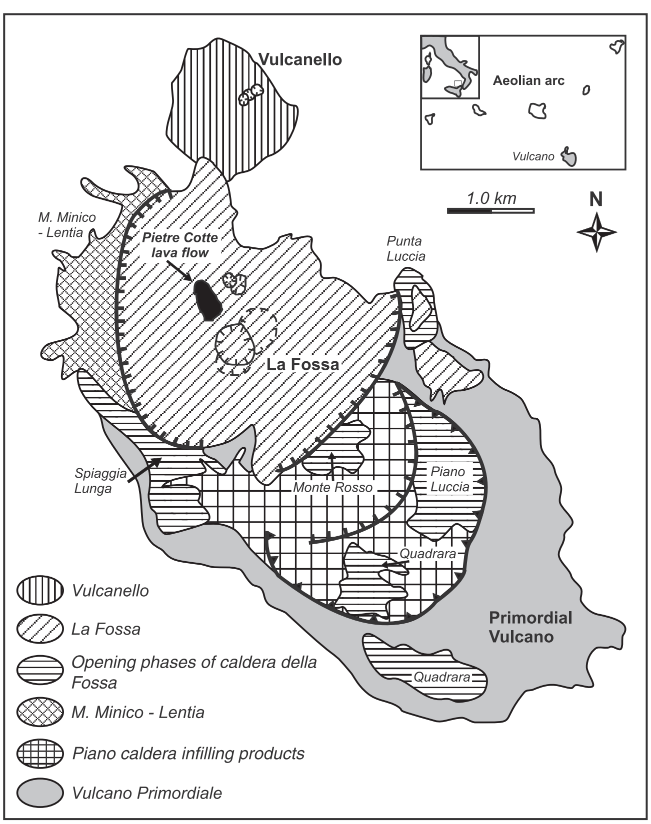

Fig. 1. Schematic geological map of the island of Vulcano (Aeolian Islands) showing the main volcanic units (modified from Keller (1980)). The Pietre Cotte lava flow studied in this paper is also indicated in the North part of the island.

Being enclave morphology a distinctive feature of the studied outcrop we focussed on quantifying the complexity of enclave boundaries. Recent works have shown that magma mixing processes generate fractal morphologies (e.g. Wada, 1995; De Rosa et al., 2002; Perugini et al., 2003a, 2003b; Perugini and Poli, 2005; Piochi et al., 2009; Morgavi et al., 2013b). It follows that fractal geometry techniques represent useful tools to quantify the complexity of mixing structures that are difficult to be quantified by classical geometrical approaches. Therefore, we used fractal geometry to quantify the complexity of enclave morphology.

One of the most used techniques to measure the fractal dimension of complex natural shapes is known as the "box-counting" method. This technique has been proven to be a robust tool to quantify mixing patterns in both plutonic and volcanic rocks (e.g. Wada, 1995; Perugini et al., 2003a, 2003b; Perugini and Poli, 2005; Piochi et al., 2009). Before applying this technique, digital images of enclaves (Fig. 4A) need to be converted to binary (black and white) images (Fig. 4B). This is done by thresholding gray scale images (Fig. 4A), to produce pictures in which the mafic and felsic magmas appear in black and white colors, respectively (Fig. 4B). Next, the interface between the mafic and felsic magma is replaced by a black line (Fig. 4C). These operations were performed using the ImageJ software (Abramoff et al., 2004).

The interface between the two magmas was used to measure the fractal dimension of enclave boundaries using the box-counting technique. With this technique a square mesh of size (r) is laid over the image and the number of boxes (N_r) containing the black pixels belonging to the interface between the two melts is counted (Mandelbrot, 1982). As an example, Fig. 4D–F reports some steps of the application of the box-counting method to a representative enclave from the Pietre Cotte lava flow. Mandelbrot (1982) showed that, for fractal patterns, the following relationship is satisfied:

$$N_r = r^{-D_{box}}. \tag{1}$$

Using logarithms, Eq. (1) can be also written as

$$\log(N_r) = -D_{box} \cdot \log(r). \tag{2}$$

Eq. (2) shows that, in order to classify a structure as a fractal, data must lay on a straight line in the log-log plot, where the fractal dimension (D_{box}) is estimated as the slope resulting from the linear interpolation of the log(r) vs. log(N_r) data.

Fig. 4G shows the variation of the number of boxes (N_r) containing the black pixels belonging to the interface between the two magmas against the box size (r); the graph in Fig. 4H displays the corresponding log-log plot. Fig. 4H shows that data points follow a linear distribution indicating that the interface is a fractal. The same features are observed for all analyzed enclaves. Fractal dimension was calculated for a total of 300 enclaves randomly sampled in the lava flow. Measurements of fractal dimension were performed using the software MorphoUt 1.0; this software has been extensively tested on structures with known fractal dimension and results are found to be very accurate (Perugini, 2002).

The uncertainty of D_{box} due to the reduction of the original grayscale images to black and white images has been checked by performing several measurements of fractal dimension of the same enclave obtained at different threshold levels. Results indicate that for a large range of threshold values (from 45 to 180, in gray values), the fractal dimension of the interface between magmas shows little variations leading to fractal dimension estimates with an error better than 0.5%. This happens because the color contrast between the enclaves and the host magma is strong enough to allow us to separate very well the interface for a