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Application of fractal fragmentation theory to natural pyroclastic deposits: Insights into volcanic explosivity of the Valentano scoria cone (Italy)

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ABSTRACT

The extent of fragmentation triggered by basaltic volcanic eruptions has been studied by analyzing the grain size distribution of natural pyroclastic deposits and applying the fractal fragmentation theory. For this purpose, 75 samples have been collected from individual layers along horizontal section of the well-exposed Valentano scoria cone (Italy). The cone is constituted by well-defined layers of fall deposits of up to 180 cm in thickness. An important feature of the stratigraphic sequence is the occurrence of several intercalated layers (called breccias) with clasts of different characteristics (angular shape, low porosity, and high crystallinity) in respect to the "normal layers". Results indicate that all achieved grain size distributions show fractal behavior and can be clearly correlated with a single fragmentation event, namely the magmatic fragmentation during the eruption. The fractal dimension of fragmentation (*D*) increases as fragmentation efficiency increases.
Values of *D* are found to vary significantly along the pyroclastic sequence defining two major trends: (1) a general, long-range increase of *D* during the course of the eruption and (2) a superimposed high-frequency oscillating variation of fragmentation efficiency. Noteworthy is the fact that the highest values of *D* are measured for pyroclastic deposits following breccia deposits. Application of a conceptual model of fractal fragmentation, as claimed by natural data, indicates that larger values of *D* have to be associated with a higher probability of fragmentation, thus suggesting that the *D* value can be used as a proxy for the "fragility" (i.e. ability to fragment) of samples. Fractal dimension of fragmentation of single layers is positively correlated with the vesicularity of clasts. This indicates that the bubble content in the ascending magma prior to and at fragmentation likely was the key factor modulating the variable fragmentation efficiency observed in the studied pyroclastic sequence. We hypothesize that the long-range variation of *D* may be associated with magma fragmentation triggered by expansion of gas bubbles progressively coalescing below solid plugs during later stages of eruptive activity, whereas high-frequency variations of *D* are interpreted as due to magma fragmentation during the "slug flow" regime characterizing the strombolian activity of the scoria cone.

1. Introduction

Since the introduction of fractal geometry techniques (Mandelbrot, 1982) there has been a growing interest in the application of these methods to a variety of geological structures and processes. From structural geology to petrology, geologists have applied fractal geometry methods and developed new techniques to quantify geological features (e.g. Sammis et al., 1986; Turcotte, 1992; Korvin, 1992; Barton, 1995; Holtz et al., 2004; Perugini and Poli, 2005; Perugini et al., 2006, 2007). The major interest of geologists about fractal methods is that they have been proven to quantify, often by a single parameter (the fractal dimension, *D*), complex processes that would be otherwise difficult to assess by classic geological techniques.

Among the research fields of Earth Sciences that benefited from fractal techniques is the one studying the development of fragmentation processes of Earth materials. In particular, grain size distributions generated by a number of geological processes, such as rock fragmentation (e.g. Matsushita, 1985; Turcotte, 1986; Sornette et al., 1990), fault gauge development (e.g. Sammis et al., 1986; Storti et al., 2003) and subsidence breccias (Barnett, 2004), have been successfully studied by applying fractal statistics.

Recently, the application of fractal techniques has been proven to be extremely efficient in the study of both morphology of basaltic ash particles (Maria and Carey, 2002, 2007) and grain size distributions resulting from volcanic eruptions both from experiments (Kueppers et al., 2006) and natural deposits (Taddeucci et al., 2004; Suzuki-Kamata et al., 2009). It is noteworthy that studies focused on the

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fractal analysis of grain size distributions mostly regarded felsic rock fragments generated by highly explosive volcanic eruptions, and studies on basaltic pyroclastic natural deposits are still lacking.

In this contribution we present new data on fragmentation processes of basaltic explosive activity. We analyze in detail the pyroclastic succession of the Valentano scoria cone (Roman Magmatic Province, Italy; Peccerillo, 2005) by applying the fractal fragmentation theory. To the best of our knowledge this is the first attempt to apply fractal analysis to the grain size distribution of basaltic natural pyroclastic deposits and thereby enhance our understanding of basaltic explosive eruptions. We use the variation of fractal dimension of fragmentation (i.e. fragmentation efficiency) to reconstruct the eruptive history of this monogenic volcanic edifice.

2. Fractal fragmentation theory

As reported by Mandelbrot (1982), Korcak (1940) performed empirical studies on the size distribution of the areas of islands and developed the empirical relationship:

$$N \approx a^{-c}, \quad (1)$$

where N is the total number of islands having sizes greater than a given comparative size, a, and c is a constant (Korvin, 1992). Mandelbrot (1982) found that c varied between island regions with c always being greater than 1/2 ($c>1/2$). In the light of fractal theory, he further realized that the size distribution of a population of islands was a consequence of fractal fragmentation and that the empirical constant c correlated with the fragmentation fractal dimension. He therefore suggested that fractal fragmentation could be quantified by measuring the fractal dimension from cumulative distributions of fragments through the equation

$$N \approx r^{-D}, \quad (2)$$

where D is the fragmentation fractal dimension and N is the total number of particles with linear dimension greater than a given comparative size, r. It is noteworthy that D derived from Eq. (2) is not a measure of irregularity, but a measure of the size–number relationship of the particle population or, in other terms, the fragmentation of the population.

Taking the logarithm of both sides of Eq. (2) yields a linear relationship between N and r with D being the slope coefficient:

$$\log(N) \approx -D\ \log(r). \quad (3)$$

The higher the value of D, the higher is the fragmentation efficiency.

It is interesting to relate Eq. (2) to a power–law relationship, which is extensively used as an empirical description for frequency–size distribution in the study of fragmentation processes (e.g. Turcotte, 1992):

$$N \approx m^{-b}, \quad (4)$$

where N is the number of fragments with mass greater than m. The constant b is chosen to fit the observed distribution. It can be showed that the constant b is equivalent to the fractal dimension D: since fragments can occur in a variety of shapes, it is appropriate to define a linear dimension r as the cube root of the volume

$$r \approx V^{1/3} \quad (5)$$

and assuming constant density it follows that $m \approx r^3$. Comparing Eq. (4) with the fractal distribution of Eq. (2) gives

$$D = -3b. \quad (6)$$

This implies that the power–law distribution of Eq. (4) is equivalent to the fractal distribution of Eq. (2):

$$N \approx m^{-b} \approx m^{-D/3} \quad (7a)$$

$$N \approx r^{-D}. \quad (7b)$$

Many size distributions in nature follow this empirical law. As an example, it was shown that fragmentation of rock material is a consequence of the scale invariance of the fragmentation mechanism, in that the zones of weakness along which fragmentation occurs can be found at all levels of scrutiny (Turcotte, 1992).

3. The Valentano scoria cone

The scoria cone of Valentano belongs to the magmatic activity of the Latera stratovolcano (Vulsini Volcanic Complex, Roman Magmatic Province, Italy; e.g. Conticelli et al., 1991; Peccerillo, 2005) that was active during a time-span from 0.43 Ma to 0.15 Ma ago (Sparks, 1975; Metzeltin and Vezzoli, 1983; Conticelli et al., 1986). After a series of highly explosive eruptions, manifested by the presence of several deposits of pyroclastic density currents (Conticelli et al., 1987), the present-day Latera caldera formed. Thereafter, several eruptions occurred from vents located along the caldera ring fault as well as inside and outside the caldera in a short time-span around 0.15 Ma (Metzeltin and Vezzoli, 1983). The scoria cone of Valentano (Figs. 1 and 2) is part of this final activity of the Latera volcano.

The Valentano deposits are mostly constituted by layers of ash and lapilli size scoria clasts, generated by strombolian eruptive activity. They are exceptionally well exposed because of recent quarrying activity (Fig. 1a) and represent an eligible outcrop to carry out a detailed investigation of an almost complete volcanic sequence. They are constituted by loose ash and lapilli deposits, which can be readily sampled (Figs. 1b and 2a). Lapilli grains generally display cuspate and sharp margins and elongated shapes; rounded grains are rarely observed. A total of 75 samples has been collected along horizontal transect (ca. 80 m), covering most of the accessible deposits forming the cone (Fig. 1a). Noteworthy is the occurrence of three layers of angular breccia deposits (Fig. 2b; average diameter of fragments is 4–8 cm) occurring in the upper half of the stratigraphic sequence. Sampled pyroclastic layers display variable thickness, from ca. 15 to 100 cm and can show massive, normal, normal to reverse, or reverse grading. A summary of characteristics of the sampled pyroclastic deposits is shown in Table 1. From the field record, each individual layer was interpreted as reflecting a single explosive episode. The hiatus between individual layers must have been fairly short, as we did not find any indication of paleosoil formation. Accordingly we hypothesize, for analogy with historical scoria cone eruptions (e.g. Schmincke, 2004), that the Valentano scoria cone is a monogenetic cone, built during eruptive activity that may have lasted for a few days to a few weeks or months.

4. Textural features of natural samples

Petrographically, scoria fragments have a porphiric texture in which phenocrysts (average length ca. 200–500 μm) of clinopyroxene, olivine, plagioclase, and phlogopite occur in a glassy groundmass (Fig. 3a–f). Phenocryst content does not vary greatly among studied samples being in the range of 3–5 vol.% (including vesicles). Microlites are mostly constituted by plagioclase and clinopyroxene crystals with acicular habit. As for phenocrysts, microlite contents are constant throughout the analyzed pyroclastic sequence with average values of 2–5 vol.% (including vesicles). Among phenocrysts, glomeroporphyric textures are typically observed and are mainly constituted by plagioclase and clinopyroxene aggregates. Some plagioclase and clinopyroxene crystals display resorbed cores on which an oscillatory