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Multifractal investigation of continuous seismic signal recorded at El Hierro volcano (Canary Islands) during the 2011–2012 pre- and eruptive phases

Luciano Telesca [a,*], Michele Lovallo [b], Joan Martì Molist [c], Carmen López Moreno [d], Rafael Abella Meléndez [d]

[a] Istituto di Metodologie per l'Analisi Ambientale, CNR, C.da S.Loja, 85050 Tito, Potenza, Italy
[b] ARPAB, 85100 Potenza, Italy
[c] ICTJA, CSIC, Barcelona, Spain
[d] IGN, Madrid, Spain

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ABSTRACT

The Multifractal Detrended Fluctuation Analysis (MF-DFA) is an effective method that allows detecting multifractality in non-stationary signals. We applied the MF-DFA to the continuous seismic signal recorded at El Hierro volcano (Canary Islands), which was affected by a submarine monogenetic eruption in October 2011. We investigated the multifractal properties of the continuous seismic signal before the onset of the eruption and after. We analysed three frames of the signal, one measured before the onset of eruption that occurred on October 10, 2011; and two after, but corresponding to two distinct eruptive episodes, the second one started on November 22, 2011 and lasting until late February 2012. The results obtained show a striking difference in the width of the multifractal spectrum, which is generally used to quantify the multifractal degree of a signal: the multifractal spectra of the signal frames recorded during the eruptive episodes are almost identical and much wider than that of the signal frame measured before the onset of the eruption. Such difference indicates that the seismic signal recorded during the unrest reflects mostly the fracturing of the host rock under the overpressure exerted by the intruding magma, while that corresponding to the eruptive phases was mostly influenced by the flow of magma through the plumbing system, even some fracturing remains, not being possible to distinguish among the two eruptive episodes in terms of rock fracture mechanics.

1. Introduction

One of the most challenging aspects in forecasting volcanic eruptions is the correct identification and interpretation of precursors in the episodes of unrest that normally precede eruptive activity. The accumulation and movement of fresh magma inside the plumbing system, and particularly when magma approaches the Earth surface, involve changes in the mechanical behaviour and state of stress of the host rock and also in the physical and chemical properties of the magma itself (Harrington and Brodsky, 2007; Jellinek and Bercovici, 2011; Lavallée et al., 2008; McNutt, 2005; Neuberg, 2000; Neuberg et al., 2000; Papale, 1999; Tárraga et al., 2014). Such changes may be detected at surface as variations of the geophysical (seismicity, surface deformation, changes in potential fields, etc.) and geochemical parameters (gas flow rate, gas composition, etc.) recorded by the volcano monitoring system that controls the activity of the volcano (Scarpa and Tilling, 1996; Sparks, 2003; Vallianatos et al., 2013). The exact meaning of these changes is not always well understood and their interpretation in terms of predictable changes (i.e. eruption precursors) in the dynamics of the magma plumbing system may entail considerable uncertainty.

However, these precursors and, consequently, these changes in the state of stress, can be more easily identified once the eruption has occurred and its products and monitoring records are analysed (e.g.: Michas et al., 2014; Tárraga et al., 2014). These tasks are normally undertaken separately, so each monitoring signal is studied independently from the others and regardless of the petrological and geochemical information provided by the study of the erupted products. But, this reduces the effectiveness of such studies because rock and magma are not regarded as parts of the same system, leading to a lack of understanding of the interdependence of the physical changes occurring in each part of the plumbing system. Recent studies, in which petrological data were examined concomitantly with geophysical data, provided significant and encouraging results on pre-eruptive and eruptive dynamics in both central volcanoes (Cashman and Hoblitt, 2004; Saunders et al., 2012) and monogenetic systems (Martí et al., 2013a).

The 2011–2012 submarine eruption of El Hierro was one of the best monitored with the most complete set of data ever recorded in monogenetic systems; furthermore, the comparison of such data with the

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* Corresponding author. Tel.: +39 0971 427277; fax: +39 0971 427271.
E-mail address: luciano.telesca@imaa.cnr.it (L. Telesca).

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erupted products has permitted to deepen the comprehension of the behaviour of the magma plumbing system during the unrest episode and the eruption (López et al., 2012; López et al., 2014; Martí et al., 2013a,b; Tárraga et al., 2014; Telesca et al., 2014).

In order to advance the knowledge of El Hierro eruption, and by extension of general understanding of eruption precursors, in this study we apply a multifractal analysis to the continuous seismic signal recorded during the unrest and eruption phases. In geophysics, multifractal analysis has been used to investigate the heterogeneity of observational signals and to characterize systems featured by very irregular dynamics, with sudden and intense bursts of high frequency fluctuations. Application of multifractal analysis to seismic sequences showed the presence of intermittency in seismicity as an effect of the lithospheric heterogeneity that occurs at many time scales (Huang et al., 1998). Multifractal fluctuations in the temporal fluctuations of regional seismicity revealed the role of aftershock clusters in increasing the intermittency of background seismicity that sharply deviates from its typical more homogeneous behaviour (Telesca et al., 2001). Multifractality in earthquake-related geoelectrical signals measured in a seismic areas in southern Italy was used as a prognostic tool of the occurrence of the largest earthquakes of that area (Telesca et al., 2005); the higher multifractal degree of geoelectrical signals before the occurrence of an earthquake was related with the fault geometry and structure, represented by a network with an anisotropic distribution of fracture orientations and consisting of fault-related structures including small faults, fractures, and veins characterized by irregular rupture propagation and non-uniform distributions of rupture velocity, stress drop and co-seismic slip. A theoretical frame to understand the physics of the earthquake-related geoelectric signals along with its fractality characteristics was presented in several studies (Colangelo et al., 2000; Tzanis and Vallianatos, 2001; Uritsky et al., 2004; Vallianatos and Tzanis, 1999; Vallianatos and Tzanis, 2003; Vallianatos et al., 2004).

Significant discrimination in terms of multifractal properties was found between the magnetic fields measured by magnetotelluric stations installed in different sites in Taiwan, revealing the response of the electromagnetic field induced from ocean (Telesca et al., 2012). The application of multifractal analysis to the geomagnetic field measured at Mt. Etna volcano (Sicily, southern Italy) before and after the onset of the strong eruption occurred on October 27, 2002 showed a significant difference between the multifractal spectra, being that before the eruption much wider than that after (Currenti et al., 2005).

In the present study, the multifractal method is used to unveil the predominant processes involved in the establishment of the feeding system and its plumbing dynamics of the El Hierro's volcanic eruption. The results obtained allow furnishing a useful instrument both for improving monitoring of active volcanoes as well as developing a deeper understanding of the pre-eruptive mechanisms which produce them.

2. Overview on El Hierro eruption

El Hierro is the youngest of the Canary Islands and its oldest subaerial rocks are dated at 1.12 Ma (Guillou et al., 1996). The island consists of a shield structure formed by different volcanic edifices and includes three rift zones along which recent volcanism is concentrated (Fig. 1). The formation of El Hierro has been affected by large sector collapses that have left scars at El Golfo, Las Playas and El Julan (Fig. 1). An unrest episode characterized by heightened seismic activity, surface deformation and gas emissions started on 17 July 2011 (López et al., 2012). Before the start of the eruption on 10 October 2011, nearly 11 000 seismic events were recorded, with local magnitudes of up to 4.3. Most hypocentres

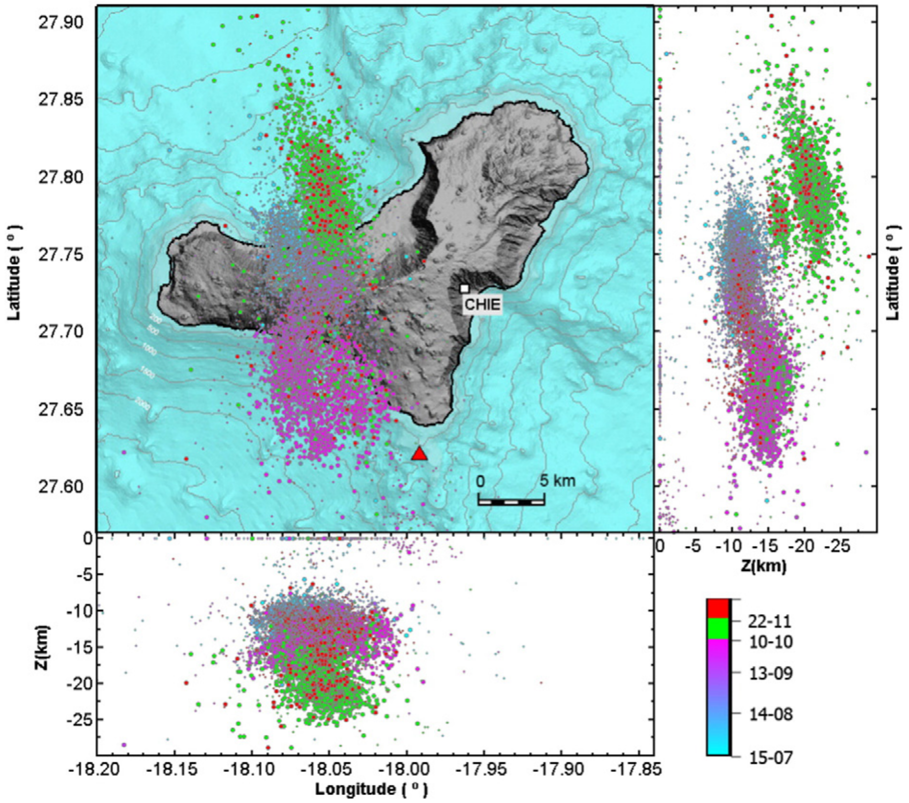

Fig. 1. Location of El Hierro and of the seismicity (circles) recorded during the unrest and the eruptive episode. Colour bar distinguishes the tree main phases: ranging from blue to purple, from 15th July 2011 to 10th October 2011; in green, from 10th October to 22nd November; in red, from then to 29th February 2012. Depth of the events is shown for vertical cross-sections in N–S direction (top right panel) and E–W direction (bottom panel). Seismic CHIE station is represented by a white square. Eruption summit location is shown with a red triangle.